UCRL-ID-154886

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

May 2003 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

R. McCallen, K. Salari, J. Ortega, LLNL; F. Browand, M. Hammache, T. Hsu, D. Arcas, University of Southern California; A. Leonard, P. Chatelain and M. Rubel, California Institute of Technology; C. Roy, L. DeChant, B. Hassan, Sandia National Laboratories; J. Ross, D. Satran, S. Walker, J.T. Heineck NASA Ames Research Center; R. Englar, GTRI; D. Pointer, T. Sofu, Argonne National Laboratory

May 1, 2003

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

May 2003
Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

Jointly written by
Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center
Georgia Tech Research Institute
Argonne National Laboratory

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on May 29-30, 2003. The purpose of the meeting was to present and discuss suggested guidance and direction for the design of drag reduction devices determined from experimental and computational studies.

Representatives from the Department of Energy (DOE)/Office of Energy Efficiency and Renewable Energy/Office of FreedomCAR & Vehicle Technologies, Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), NASA Ames Research Center (NASA), University of Southern California (USC), California Institute of Technology (Caltech), Georgia Tech Research Institute (GTRI), Argonne National Laboratory (ANL), Clarkson University, and PACCAR participated in the meeting. This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, provides some highlighted items, and outlines the future action items.

Introduction, Overview of the Project, and Summary

The meeting began with an introduction by the LLNL Program Leader for Energy Technology & Security Program, Cindy Atkins-Duffin. The DOE Program Lead, Sid Diamond, followed the introduction with a discussion on budget and some insightful information on fuel consumption and financial impact. Per Sid, an estimated total savings of $1.5 billion per year can be recognized in the US alone for a 6% reduction in fuel use. This reduction represents 1% of all fuel use in the US.

The presentations and discussion on the first day of the meeting provided experimental and computational findings and specific guidelines for

- Drag reduction devices,
- Experimental testing, and
- Computational modeling.

The technical presentations on the second day of the meeting included a review of experimental results and plans by GTRI, USC, LLNL, and NASA Ames, the computational results from LLNL and SNL for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) model, from ANL for the Generic Conventional Model (GCM, a.k.a. SLRT), by LLNL for the tractor-trailer gap and trailer wake flow investigations, and turbulence model development and benchmark simulations being investigated by Caltech. USC is also investigating an acoustic drag reduction device that has been named 'Mozart', GTRI continues their investigation of a blowing device, and LLNL presented their idea for a gap drag reduction device. Also discussed were future interactions with the Industry Consortium being lead by Bob Clarke of the Truck Manufacturers Association (TMA). Details are provided in the attached viewgraphs.

Project Goals, Deliverables, and Future Activities

Based on discussions at the Meeting, the project goals remain unchanged:

- Perform heavy vehicle computations to provide guidance to industry,
- Using experimental data, validate computations,
- Provide industry with design guidance and insight into flow phenomena from experiments and computations, and
- Investigate aero devices (e.g., boattail plates, side extenders, blowing and acoustic 'Mozart' device).

The following additional activities were identified and the responsible individuals are indicated:

1) Write white paper to OEMs participating in DOE Industry Consortium on recommended drag reduction devices and suggested road testing (R. McCallen)
2) Several Team members to attend DOE Industry Consortium meeting to be held some time during Fall 2003 (J. Ross)
3) Investigate the aerodynamic drag contribution due to wheel wells and underbody flow (K. Salari)
4) Begin investigation of wheel splash and spray (F. Browand)
5) Consider application of the Consortium's expertise and tools to the area of railcar and locomotive aerodynamic drag (J. Ross)
6) Publish data (NASA, USC, GTRI, LLNL Teams)

7) Publish computations (LLNL, ANL, SNL, Caltech Teams)

Technical Discussion Highlights

In this section, we very briefly review the major results presented and discussed at the meeting, with a focus on new information not previously presented. See attached viewgraphs for additional results and details.

Drag Reduction Devices

Fred Browand of USC provided an overview of the Team's work on aerodynamic drag reduction devices, along with experimental and computational results and specific guidelines. Bob Englar of GTRI facilitated the discussion session and Jason Ortega of LLNL and Tsun-Ya Hsu of USC constructed a summary of the presentation and discussion. The following summarizes the major highlights.

There are three areas identified for aero drag reduction and several drag reduction devices were discussed

- Tractor-Trailer Gap: Stabilizing devices, cab extenders
- Wheels/Underbody: Skirts/lowboy trailer ($\Delta C_D \sim 0.05$), splitter plate
- Trailer Base: Boattail plates ($\Delta C_D \sim 0.05$), base flaps ($\Delta C_D \sim 0.08$), rounded edges, and pneumatics

Base flaps, as shown in Figure 1, are expected to provide 50% more drag reduction than boattails. For a tractor-trailer with a $C_D = 0.55$ the percent drag reduction ($\Delta C_D/C_D$) utilizing base flaps and side skirts and/or a low boy is estimated at 22 to 25 percent. Thus, the use of base flaps and skirts would provide an 11 to 12 percent fuel savings which should result in a $3 billion per year fuel cost savings in the US. (Note that the cost of the device and possible maintenance over the year should also be considered for determining the overall cost savings to the fleet owner.)

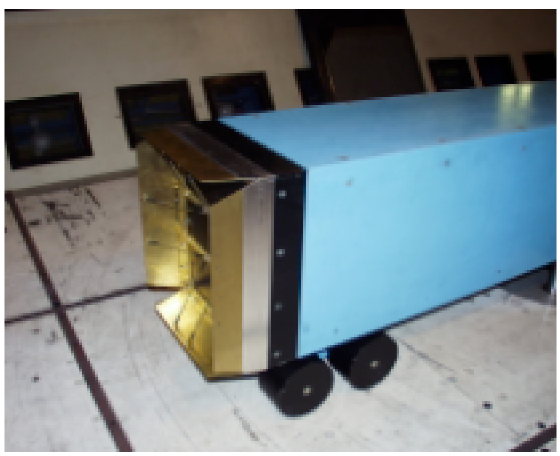


Figure 1. Base flaps (gold colored) mounted on back end of trailer (blue) in NASA's 12-ft pressure wind tunnel.

The base flaps are simple flat plates mounted on the edges of the back end of a trailer. The lengths of the plates match the dimensions of the trailer base (two 11.5 ft long plates on the sides and two 8.5 ft long plates on the top and bottom). The width of the plates or how much they protrude from the trailer is about 1/4 the width of the trailer or about 2 feet. Tilting the flaps about 20 degrees inward away from being flush with the trailer sides appears to provide the optimum drag reduction. The optimum flap angle for an on road vehicle is yet to be determined, but we expect it to be near 20 degrees.

Road testing the drag reduction devices is needed to determine

- On road fuel savings,
- Optimal flap deflection angle for various tractor-trailer geometries,
- Optimal flap shape,
- Optimum skirt height,
- Durability, practicality, safety, ease of operation of proposed devices, and
- Impact on truck braking capability.

It is recommended that road testing include

- Instantaneous broadcast fuel rate (1/2 second updates),
- Repeated forward and back trip runs over known, instrumented highways (e.g., South-to-North and North-to-South runs over a portion of California I-15), and
- Base flap device evaluated in close-following combinations of 1 to 3 trucks.

To recognize these levels of fuel savings by the most effective use of drag reduction devices, the involvement and acceptance by tractor manufacturers, trucking associations, fleet owners, and drivers is critical. It is thus important to

- Solicit input and feedback from these organizations for design of base flaps and low boy and/or skirt construction,
- Demonstrate "actual" fuel savings from road tests and interest OEMs in doing testing, and
- Make site visits or attend DOE's Industry Consortium's Working Group meetings to encourage input and feedback.

Suggestions included encouraging the DOE Industry Consortium to road test base flaps and skirts or low boys as part of their DOE funded effort. Another suggestion is to contract with California Partners for Advanced Transit and Highways (PATH) to perform the proposed road tests as part of their 3-truck demonstration platoon.

Experimental Findings and Suggested Guidance

Dale Satran and J.T. Heineck of NASA provided an overview of the Team's experimental results and specific experimental guidelines on achieving accurate predictions. Fred Browand of USC facilitated the discussion session and Jason Ortega of LLNL and James Ross of NASA constructed a summary of the presentation and discussion. The following summarizes the major highlights.

Experiments have been conducted on a Generic Conventional Model (GCM) in the NASA Ames 7-ft x 10-ft wind tunnel for Reynolds numbers (Re) of 1 million based on the width of the trailer, which corresponds to a full-scale vehicle traveling at roughly 15-

mph. Experiments have also been performed on the GCM geometry in the NASA Ames 12-ft pressure wind tunnel (PWT) for Re of 1 and 6 million, where the later corresponds to a full-scale vehicle traveling at 80-mph. Geometry configurations included the addition of tractor side extenders, a low boy trailer, and boattails and angled flaps on the trailer's trailing edge. The results in the PWT are obtained for a constant Mach number (Ma = 0.15) by pressurizing the tunnel. This allows for the determination of Re and geometry effects. Yaw angles were varied from +14 to -14 degrees measured from the vehicle length axis and wind direction so that accurate wind-averaged drag could be determined, in addition to determining the effect of yaw angle. The following is a list of experimental techniques and measurements:

- Internal balance measured the vehicle forces and moments
- Load cells measured the drag for the body axis and yawing moment of the tractor
- Static pressure taps on the model (476) and taps on the walls and floor (368) measured static pressure conditions
- Unsteady pressure transducers (14) provide a pressure time history on the surface of the vehicle
- Three-dimensional particle image velocimetry (PIV) provided a time history of the velocity field on planes in the wake of the vehicle and in the tractor-trailer gap.

Drag measurements alone are not sufficient to provide an understanding of the impact of geometry modifications and direction for design improvements. It is recommended that advanced measurement techniques like PIV and pressure sensitive paint (PSP) be included. These advanced techniques provide important information on the global and local structure of the flow and can provide clear design direction.

The following are the determined Re effects (note: Re is based on the width of the trailer and freestream velocity):

- Re effects on C_D are in general minimal for experiments with Re above 1 million. This finding supports the common use of scaled down vehicles and Re below typical highway Re for experimentation.
- It should be noted that some Re influence was apparent on the flow structure in the tractor-trailer gap and the back end of the trailer. It was most apparent in the upper portion of the flow region in the gap and in the wake. Thus, some inaccuracies should be considered when evaluating gap and wake drag reduction devices at lower than highway Re. Low Re experiments should provide ball park estimates, but accurate optimization of devices may require road testing.
- Edge radius effects and/or the cleanliness of the vehicle upstream flow are critical to achieving accurate predictions. Corner radii on the leading edge of the vehicle should provide Re > 50,000, based on corner radius and tunnel freestream velocity. Tripping the flow at the vehicle leading edge may also be required to avoid flow separation.

Computational Findings and Suggested Guidelines

Kambiz Salari of LLNL provided an overview of the Team's computational results and specific computational guidelines on achieving accurate flow simulations. Basil Hassan of SNL facilitated the discussion session and Mike Rubel of Caltech and David Pointer of ANL constructed a summary of the presentation and discussion. The following summarizes the major highlights.

Team members from LLNL, SNL, ANL, and Caltech are investigating a wide range of turbulence models including steady and unsteady Reynolds-averaged Navier-Stokes (RANS and URANS, respectively), large-eddy simulation (LES), and hybrid methods that use a combination RANS and LES models in the simulation. In addition, various numerical approaches are being considered including finite volume, finite element, and vortex methods. The focus of the presentation and discussion of this working meeting was steady RANS with and without the use of wall functions. Wall functions provide an approximation to the flow field in the wall region and the flow field is not resolved.

The following are the general observations and guidelines for steady RANS modeling:

- Conclusions on predictive capability of a turbulence model can only be determined with grid converged solutions. Predicted flow structures in separated regions, like the trailer wake, vary significantly with grid refinement. Variation in overall drag is not substantial but still apparent with grid refinement.
    - When using wall functions, the first wall point should be held fixed while refining the grid (i.e., the distance from this grid point to the wall should not change), but it is appropriate to decrease the width of the wall elements while refining the grid (i.e., refinement in direction tangent to walls).
- The computed overall vehicle drag is highly dependent on the choice of turbulent steady RANS model. Solutions may disagree with measurements by 0.5 to 50% for 0 degree yaw and by even higher percentages at yaw angles. Thus, the performance of steady RANS models for a given geometry is not predictable and experimental results to determine ball park accuracy is critical when relying on steady RANS for design guidance.
- Steady RANS models generally do a good job predicting the flow on the front and sides of the vehicle, where the flow stays attached and does not exhibit separation and recirculation zones.
- The flow structure in the trailer wake presented by the time-averaged experimental data does not compare with that computed with the steady RANS models. The trailer wake is a region of transient full flow separation and large recirculation zones. Thus, use of steady RANS to evaluate drag reduction devices in the trailer wake and tractor-trailer gap may provide inaccurate design guidance.

Near term plans are to organize similar types of guidelines related to the performance of unsteady RANS, LES, and hybrid models.

Truck Aero Team Meeting Attendees

LLNL, Livermore, CA

May 29-30, 2002

Attendee	Organization	e-mail address and phone
Kim Abbott	DOE	kim.abbott@oak.doe.gov
Larry Dechant	SNL	ljdecha@mailgate.sandia.gov, (505)844-4250
Sid Diamond	DOE	sid.diamond@ee.doe.gov, 202-586-8032
Bob Englar	GTRI	bob.englar@grti.gatech.edu, 770-528-3222
Paul Hancock	PACCAR	Paul.Hancock@PACCAR.com, (360) 757-5462
Basil Hassan	SNL	bhassan@sandia.gov, 505-844-4682
J. T. Heineck	NASA ARC	jheineck@mail.arc.nasa.gov, 650-604-0368
Tsun-Ya Hsu	USC	tsunyah@spock.usc.edu, 213-740-0516
Rose McCallen	LLNL	mccallen1@llnl.gov, 925-423-0958
Jason Ortega	LLNL	ortega17@llnl.gov, 925-423-3824
David Pointer	ANL	dpointer@anl.gov, 630-252-1052
Jim Ross	NASA ARC	jcross@mail.arc.nasa.gov, 650-604-6722
Jules Routbort	ANL/DOE	routbort@anl.gov, 630-252-5065
Chris Roy	SNL	cjroy@sandia.gov, 505-844-9904
Mike Rubel	Caltech	mrubel@caltech.edu, 626-395-8310
Kambiz Salari	LLNL	salari1@llnl.gov, 925-424-4635
Dale Satran	NASA ARC	dsatran@mail.arc.nasa.gov, 650-604-5879
Ken Visser	Clarkeson	visser@clarkson.edu, (315)268-7687

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory
Livermore, CA

May 29, 2003

Purpose of Meeting
Presentation & discussion of overall experimental and computational findings related to the aerodynamics of heavy vehicles

•

Suggested guidance and direction for design of drag reduction devices, as well as experimental and computational studies

Discussion of future activities

Introduction

Welcome	Cindy Atkins-Duffin (LLNL, Energy Technology & Security Program)
Words of wisdom	Sid Diamond (DOE), Jules Routbort (DOE/ANL)
Introduction	Rose McCallen (LLNL)

Drag Reduction Devices

Presentation	Fred Browand (USC)
Facilitated discussion	Bob Englar (GTRI)
Summary	Jason Ortega (LLNL) and Tsun-Ya Hsu (USC)

Experimental Findings and Suggested Guidelines

Presentation	Dale Satran (NASA)
Facilitated discussion	Fred Browand (USC)
Summary	Jason Ortega (LLNL) and Jim Ross (NASA)

Computational Findings and Suggested Guidelines

Presentation
Kambiz Salari (LLNL)

Facilitated discussion	Basil Hassan (SNL)
Summary	Mike Rubel (Caltech) and David Pointer (ANL

DOE Industry Consortium: Vision, Plan, and Activities

Informal discussion	Paul Hancock (PACCAR)

Other

Informal discussion	Ken Visser (Clarkson University)

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory
Livermore, CA

May 30, 2003

Purpose of Meeting
Status report
FY04 plans and budget

Introduction

Introduction	Rose McCallen
More words of wisdom	Sid Diamond (DOE), Jules Routbort (DOE/ANL)

Experiments and Devices

GTRI	Bob Englar
USC	Fred Browand
LLNL	Jason Ortega
NASA	Jim Ross

Computations and Devices

Caltech	Mike Rubel
SNL	Basil Hassan
LLNL	Kambiz Salari
ANL	David Pointer

Wrap-up

Discussion	All

‘Working Group Meeting’
Consortium for Aerodynamic Drag of Heavy Vehicles
Department of Energy, Office of FreedomCAR & Vehicle Technologies
May 29, 2003

Rose McCallen, Kambiz Salari, Jason Ortega — University of California Lawrence Livermore National Laboratory

Chris Roy, Larry DeChant, Basil Hassan — Sandia National Laboratories

James Ross, Dale Satran, J.T. Heineck, Steve Walker — National Aeronautics & Space Administration

Fred Browand, Mustapha Hammache, Tsun-Ya Hsu, Diego Arcas — USC University of Southern California

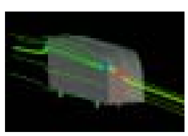
Anthony Leonard, Mike Rubel, Philippe Chatelain — Caltech California Institute of Technology

Robert Englar — Georgia Tech Research Institute

David Pointer, Tanju Sofu — Argonne National Laboratory

*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

GOOD SCIENCE

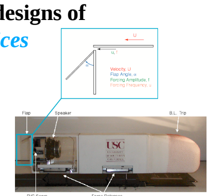


LLNL, SNL, ANL, Caltech
High quality numerical *computations*
Guidance on computational tools

NASA, USC
Data base of high quality wind tunnel *experiments*

USC, NASA, LLNL, SNL
Comparisons and analyses
Insight into flow phenomena

USC, GTRI, LLNL
Concepts and designs of aero *devices*



TEAM, Industry
Information exchange

FREIGHTLINER PACCAR Inc VOLVO

INDUSTRY SUPPORT

NEAR-TERM BENEFIT

Drag Reduction Devices

Discussion of *selected* recent work

University of California
Lawrence Livermore National Laboratory

USC UNIVERSITY OF SOUTHERN CALIFORNIA

National Aeronautics & Space Administration

Georgia Tech Research Institute

Drag Reduction Devices

- No aero shield
- Huge radiator
- Many corners
- Protruding lamps, tanks, pipes, etc.

Drag Reduction Devices

- Built-in aero shield
- Small radiator
- Rounded corners
- Recessed lamps, tanks, etc.

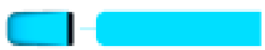
Drag Reduction Devices

Gap	Wheels & underbody	Trailer base
cab extenders	skirts low boy trailer	base blowing boat-tail/flaps

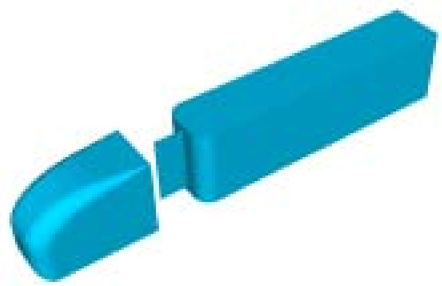
LLNL Gap Add-on Device

The gap add-on device will stabilize the gap flow, for the gap distance above the critical limit, and in turn reduce the total aerodynamic drag of the vehicle

Side view



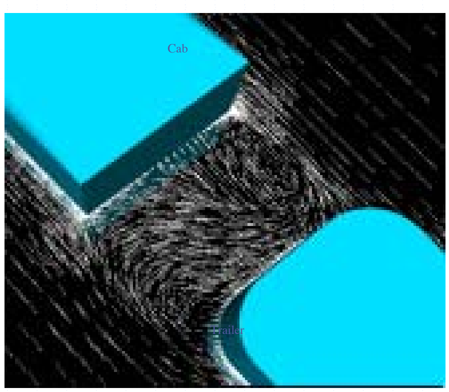
Top view



USC Modified GTS with a Gap Add-on Device

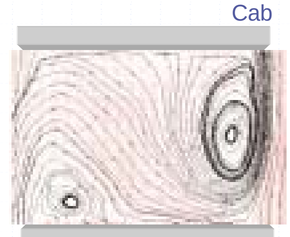
Gap Flow Investigation , 0° yaw

Non-Dimensional Gap Distance of 0.72



OVERFLOW Computation, 50% Height

Cab

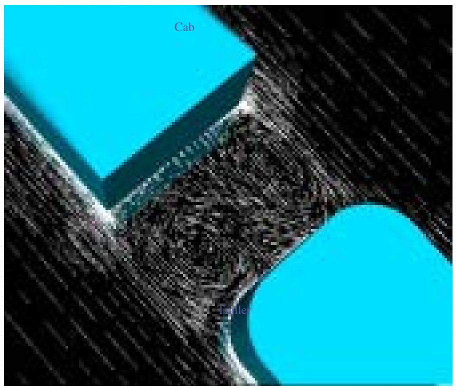


Trailer

USC Experiment, 50% Height

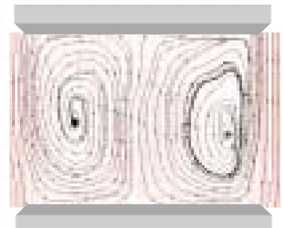
$$\mathrm{Re} = \frac{U\sqrt{A}}{n} = 300{,}000$$

Gap Flow Investigation , 0° yaw, ...



OVERFLOW Computation, 50% Height

Cab

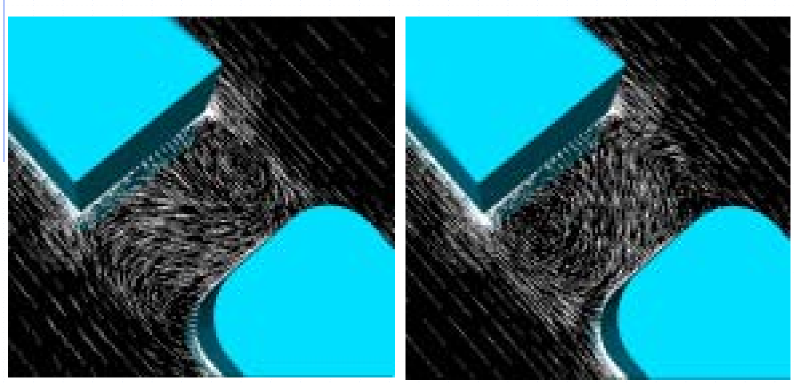


Trailer

USC Experiment, 50% Height

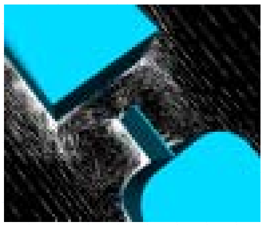
Gap Flow Structure, 0° yaw

Asymmetric flow structure in the gap present on both side

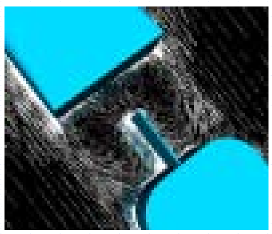


Non-dimensional gap distance of 0.72, USC tunnel condition

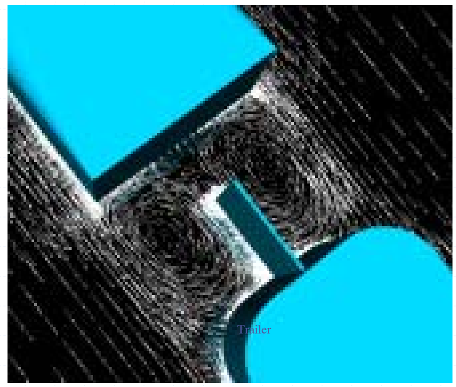
Gap Flow Structure with the Add-on Device, 0° yaw



Horizontal plane, 25% height



Horizontal plane, 75% height



Velocity vector plot, horizontal plane, 50% height

Drag Reduction Devices

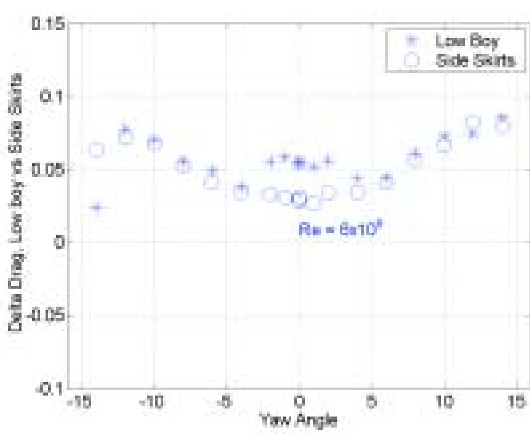
Gap	Wheels & underbody	Trailer base
cab extenders	skirts low boy trailer	base blowing boat-tail/flaps

Drag Reduction Devices, NASA Tests

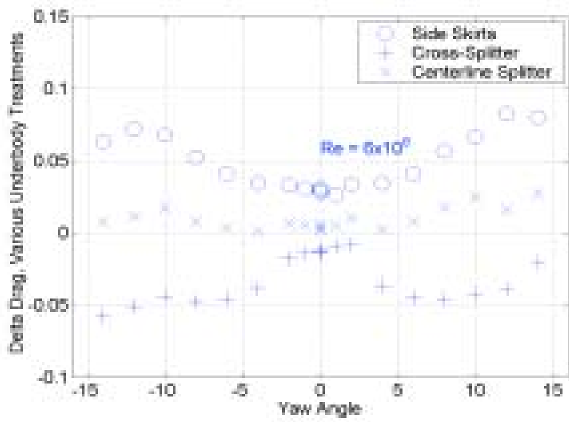
12 ‘ pressurized tunnel—full-scale Re

Re = 0.5 –6 x 10^6

Drag Reduction Devices



Drag Reduction Devices



Drag Reduction Devices

Gap

cab extenders

Wheels & underbody

skirts
low boy trailer

Trailer base

base blowing
boat-tail/flaps

Drag Reduction Devices, GTRI Road Tests

Rear View with Jets Blowing

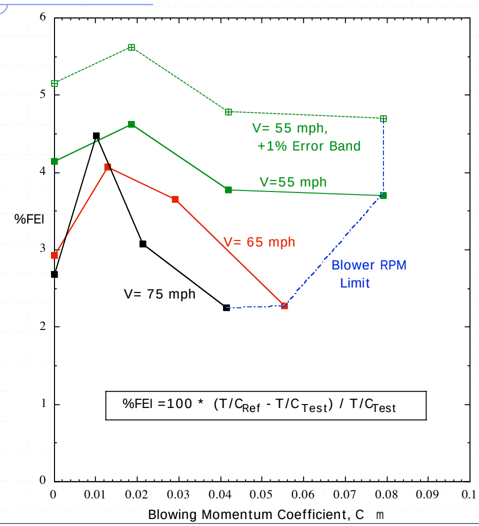
Close-up of Tufts
Showing Jet Turning

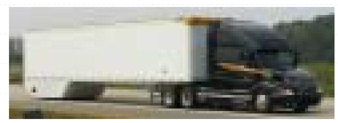
Drag Reduction Devices, GTRI Road Tests

Configuration	WindTunnel C_D	% C_D Change	% Equiv. GPM Reduction	Road Test Run No.	% GPM Reduction	% Equiv. C_D Change	% MPG Increase
Baseline, No Gap, Sq. LE & TE	0.627	0	0.0	13 (Gap)	0.00	0.00	0
Unblown PHV, Cmu=0	0.57	-9.1	-4.6	9	-10.21	-20.42	11.37
PHV,4 Slots Cmu=0.05	0.44	-29.8	-14.9	5	-13.27	-26.54	15.30

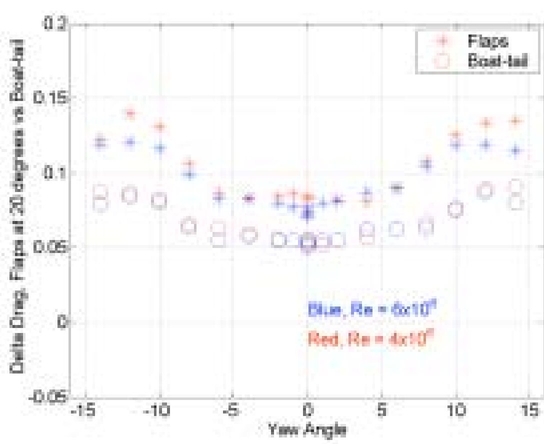
Tuning Test Results (V=65 mph), Comparison to GTRI Wind Tunnel Results

Drag Reduction Devices, GTRI Road Tests





Drag Reduction Devices, NASA Tests

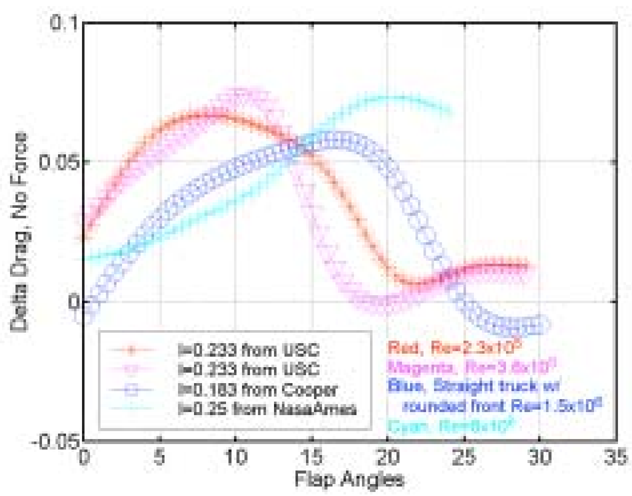


Drag Reduction Devices, USC Tests

Base flap attachment, typical

Smooth forebody,
Re ª 0.2 – 0.3 x 10^6

Effect of Base Flaps on Drag Reduction –Three Experiments



Drag Reduction Devices

Summary of two passive devices

Base flaps		DC_D ª 0.08
Side skirts/Low boy		DC_D ª 0.035 – 0.06
	TOTAL	DC_D ª 0.12 – 0.14
	For	C_D ª 0.55
		DC_D/C_D ª 22% - 25%
	Fuel savings	ª 11% - 12%

Should we conduct over-the-road tests of base flaps?

Drag Reduction Devices

Over-the-Road Test of Base Flaps and/or trailer skirts

(1) Interest trailer manufacturer to provide design input for base flap construction and/or skirt construction.

(2) Interest OEM to do testing.

(3) Contract to California PATH to make part of their 3-truck demonstration platoon.

- Instantaneous broadcast fuel rate (1/2 second update)
- Repeated S-to-N and N-to-S runs over known, instrumented
  portion of I-15
- Base flap device evaluated in close-following combinations of 1-3 trucks

Drag Reduction Devices ~ Facilitated Discussion of

- **PASSIVE**
  - **Boat Tails, Plates, Angle Plates, “Silent Mozart”**
  - **Gap Vortex Stabilizer**
  - **Gap Drag Reduction, Impact on aft devices**
  - **Underbody**
  - **Drag due to Yaw & Directional Stability**
  - **Reduced Splash & Spray**
  - **Many of these already evaluated**
- **ACTIVE**
  - **Pneumatic HV and SUV(separation prevention, Cp recovery)**
  - **Forcing (Mozart, oscillatory) (separation prevention)**
  - **Elimination of Drag due to Yaw**
- **Multi-Purpose Aerodynamic Devices**
  - **Drag reduction, or increase for braking**
  - **Moment Control for Stability & Handling**
  - **Other Aero Forces**
- **DISCUSSION**

DISCUSSION~ Drag Reduction Devices

- Relative Gains from Each Device or Type
- Related Research/Developments already conducted-
  What can we learn?
  If not operational at this time, WHY?
- Relative Problems
  - Gap Effects on Trailing-edge Devices
  - Scaling: Model results less than full-scale
  - Real-World Applications
  - User Acceptance
  - Cost vs Payoff
  - Single or Multi-purpose Devices
- WHERE DO WE GO FROM HERE??

Summary

- Three areas identified for ***aerodynamic drag reduction***
  - ***Gap***: stabilizing devices, cab extender, splitter plate
  - ***Wheels/underbody***: skirts, lowboy trailer ($DC_d \sim 0.05$)
  - ***Trailer base***: boattail plates ($DC_d \sim 0.05$), base flaps ($DC_d \sim 0.08$)
- Overall estimated fuel savings of **11-12%!!!**

Discussion Topics

- Next logical step of ***road testing*** drag reduction devices to determine:
  - ***Actual*** fuel savings
  - ***Optimal flap deflection angle*** for various tractor/trailer geometries
  - ***Optimal flap shape***
  - ***Durability, practicality, safety, ease of operation*** of proposed devices
  - Impact on truck ***braking capability***
- Further ***refinement of devices***: mini-skirts, gap stabilizer

Discussion Topics

- ***Involvement*** and ***acceptance*** by tractor manufactures, trucker associations, fleet owners
  - Demonstrating ***actual fuel savings*** from road tests
  - Getting ***input*** and ***feedback*** from these organizations
  - ***Site visits*** to these organizations

Experimental Findings of the Generic Conventional Model (GCM) in the NASA Ames 12-Foot Pressure Wind Tunnel

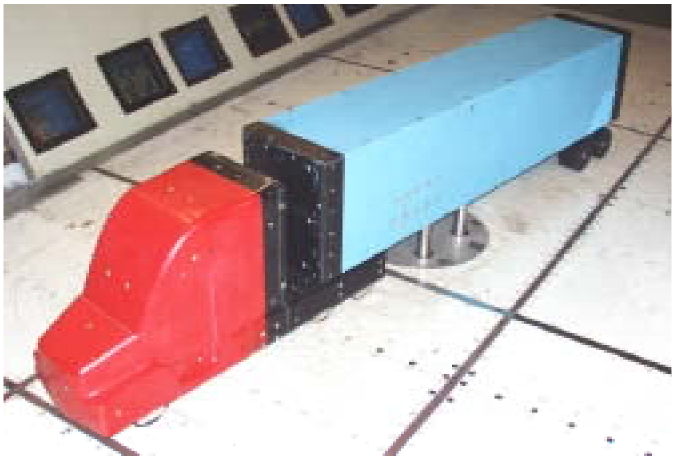
Dale Satran
NASA Ames Research Center
Dale.R.Satran@nasa.gov
650-604-5879

Heavy Vehicles: Aerodynamic Drag
May 29, 2003

Outline

- **Model Geometry**
- **Test Techniques**
- **Test Conditions**
- **Results**
- **Recommendations**

Basic Model



Model Geometry

- Generic tractor with engine in front
- Scale: 0.125
- Cross sectional area = 1.66 sq. ft.
- Trailer width = 12.75 in.
- Model length = 96 in.
- Model geometry has been digitized
- Side extenders varied from 1 in. to 3 in.

Test Techniques

- Internal balance measured the vehicle forces and moments
- Load cells measured the drag and yawing moment of the tractor
- 476 static pressure taps on the model and 368 taps on the walls and floor
- 14 unsteady pressure transducers
- Particle image velocimetry (3-D)

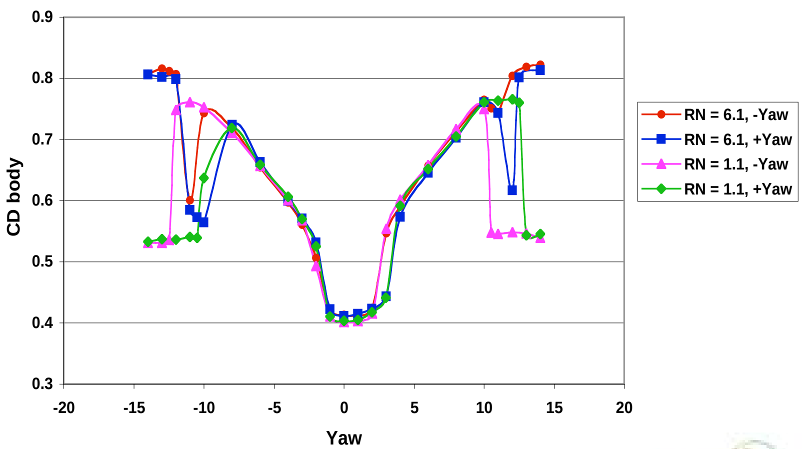
Test Conditions

- Primary Conditions
  - Mach Number = .15
  - Reynolds Number = 1 to 6 million based on trailer width
  - Loads are 6 times larger for 6 million Reynolds Number runs than for 1 million runs
- Yaw angles 14° to -14°

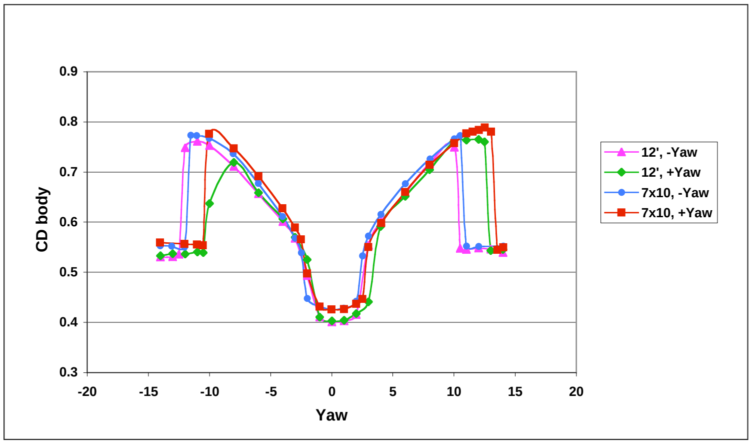
Results

- Drag results are for the body axis system
- Model geometries
  - Basic
  - Side Extenders

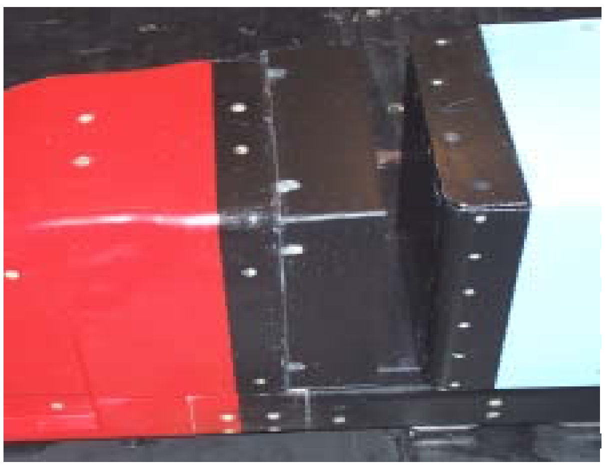
Basic Model - Hysteresis



Basic Model - Tunnel Comparison



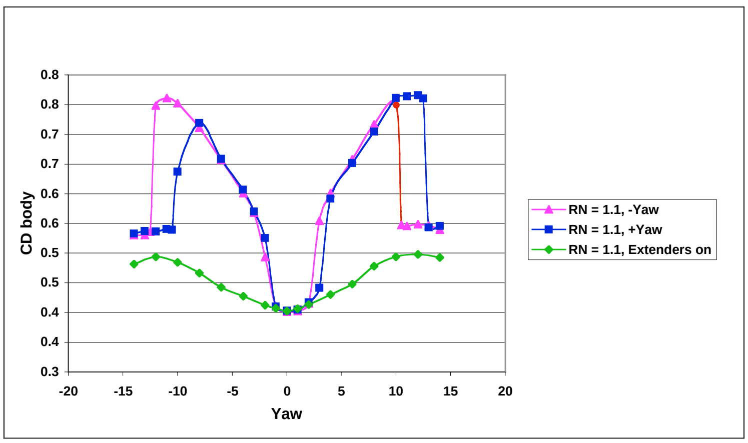
Side Extenders



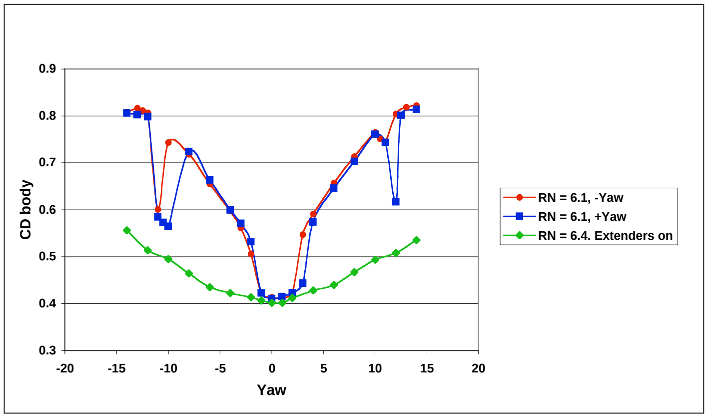
Side Extenders

- Varied from 1.5 inches to 3 inches
- Based on 7x10 results, 2.5 inches was optimum at 1 million Reynolds Number
- Based on 12' results, 3 inches was optimum at 6 million Reynolds number

Side Extenders

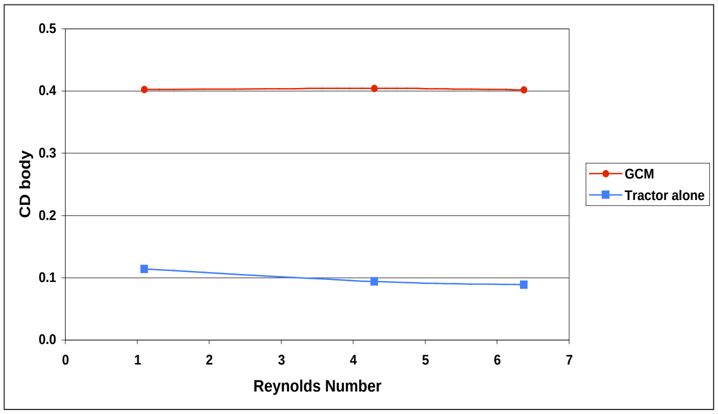


Side Extenders



Experimental Physics Branch

Reynolds Number Effect

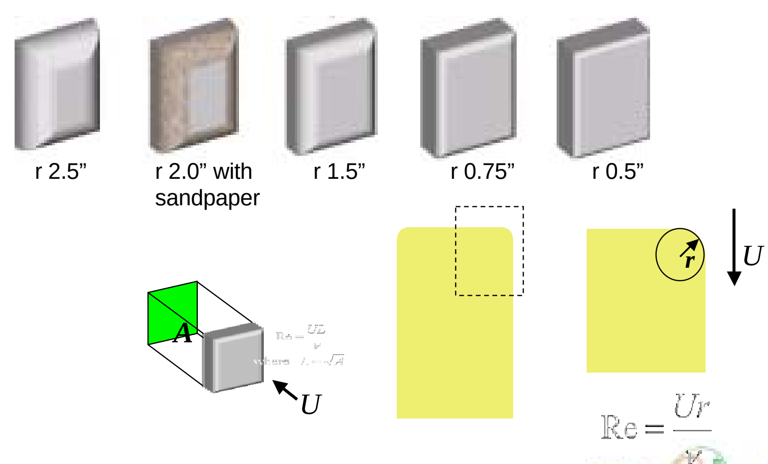


Experimental Physics Branch

Wind Averaged Drag Coefficient

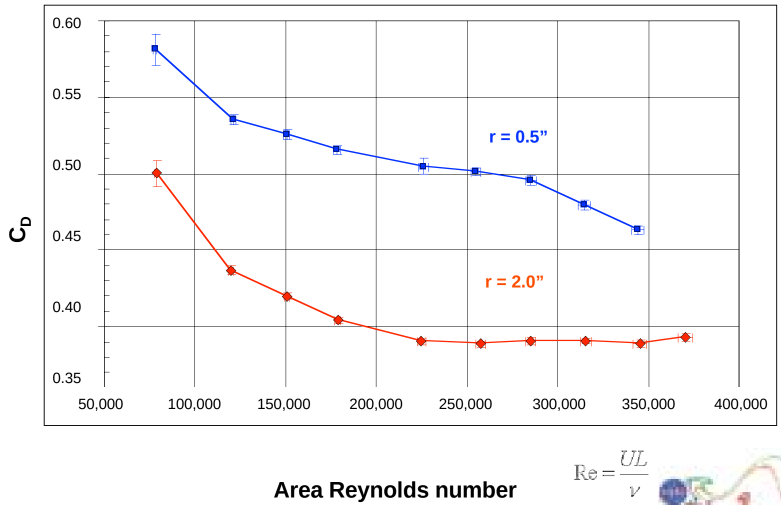
- For 55 mph vehicle speed with a 7 mph wind speed
  - Yaw angles vary from 1.7° to 7.2°
- For 75 mph vehicle speed with a 7 mph wind speed
  - Yaw angles vary from 1.2° to 5.2°
- For 30 mph vehicle speed with a 7 mph wind speed
  - Yaw angles vary from 2.8° to 13.5°

Front-End Radius of Curvature



$$\mathbb{R}\mathrm{e} = \frac{Ur}{\nu}$$

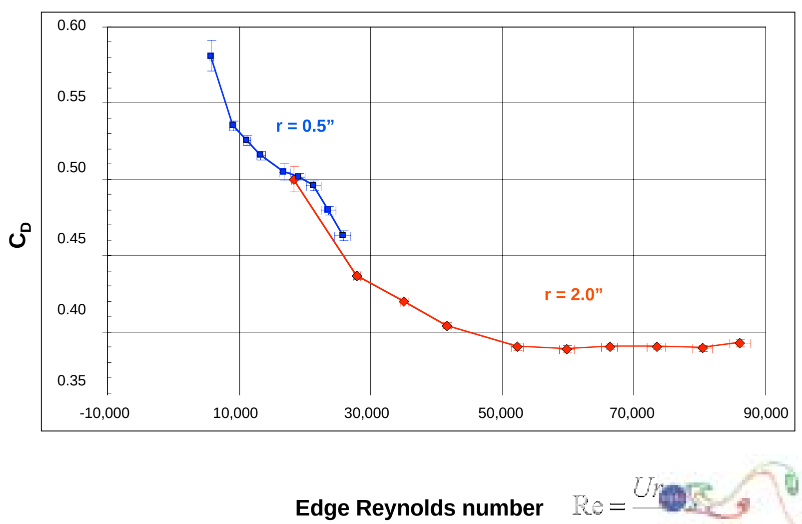
Drag of Isolated Cab



$$\mathrm{Re} = \frac{UL}{\nu}$$

where $L = \sqrt{A}$

Drag of Isolated Cab



$$\mathrm{Re} = \frac{Ur}{\nu}$$

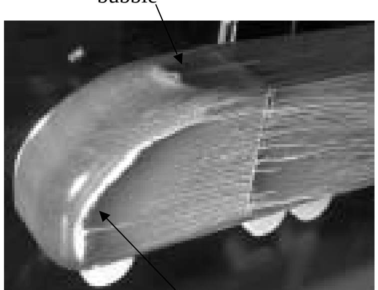
Low Speed, Small Scale Wind Tunnel Tests

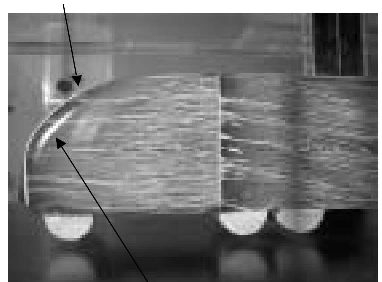
- **Provide a relatively** *simple* **and** *inexpensive* **means for testing the effectiveness of** *add-on drag reduction concepts*
- *Flexibility* **to test a** *significant number* **of configurations**
- *Ability* **to obtain** *wind-averaged drag coefficients*
- *Better understand* **the fluid mechanics of the complex, 3-D flow field about the tractor/trailer**

Means of Ensuring Attached Flow on the MGTS Tractor

flow separation bubble

boundary layer trip





flow separation bubble

attached flow

- **Follow-on of the USC effort in keeping the flow attached to the tractor**

Experimental Physics Branch

Recommendations

- Minimal Reynolds Number effects above 1 million
- Drag measurements alone are not sufficient
- Advanced instrumentation for global measurements (PIV & PSP)
- Critical model sizes (separation issues)
- Optimization maybe slightly off based on Reynolds numbers less than full scale

Experimental Physics Branch

The Measurement of Gap Flows of the GCM in the 12' Pressure Tunnel using Three-component PIV

James T. Heineck, Stephen M. Z. Walker, Dale Satran,
NASA Ames Research Center

United Engineering Foundation Conference
Aerodynamics of Heavy Vehicles: Trucks, Buses and Trains
Pacific Grove , CA December 2-6, 2002

PIV Measurement Goals

Produce three-component vector data for CFD validation and determining the flow physics

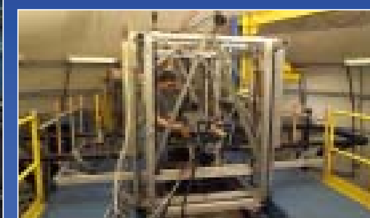
Measure the gap and wake flows at 1 million and 5 million Re, with and without gap extensions

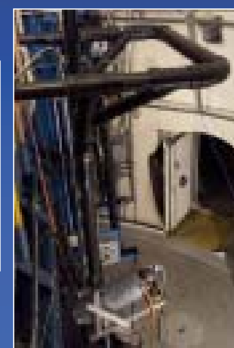
Measure the regions of interest at three horizontal locations and 2 yaw angles.

Ames Research Center

Design Parameters of the PIV System

- Only horizontal planes are possible
- Use glass side extenders for nearly full optical coverage
- Move the set-up remotely for each level and yaw angle





Ames Research Center

Components and Specs of the PIV System

Cameras: 1024x1384, cooled cross-correlation type, gap spatial resolution of 0.25 mm/pixel

Lasers: Two units, each 125 mJ/pulse, dual oscillators

Optics: Two set of sheet forming optics, two set of large first-surface mirrors

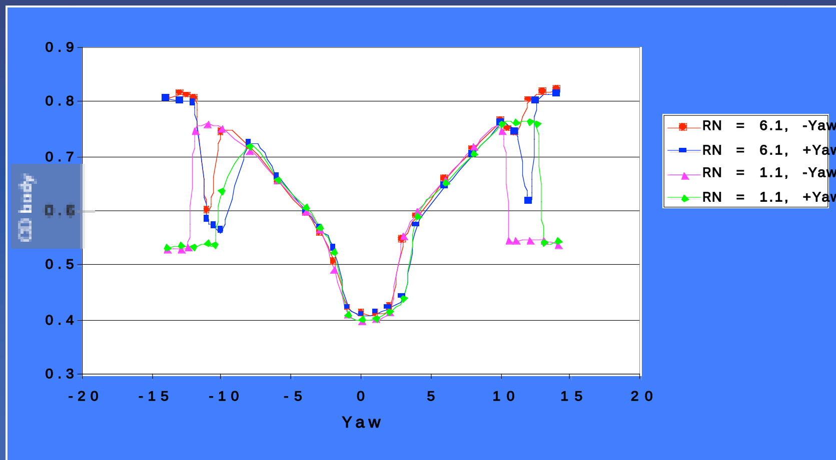
Traverses: Vertically driven laser/optics/camera structure, rotating camera structure, rotating beam-steering mirrors, all remotely controlled

Seeding: Smoke generator using mineral oil media producing 0.5-1.0 micron particle

Vector Window: 24 x 24 pixels (6.2 mm^2 in gap area), 50% window overlap, giving a vector every 3 mm

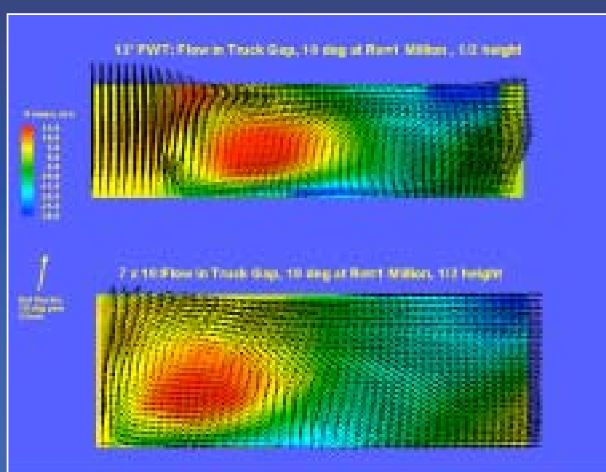
Ames Research Center

Basic Model - Hysteresis

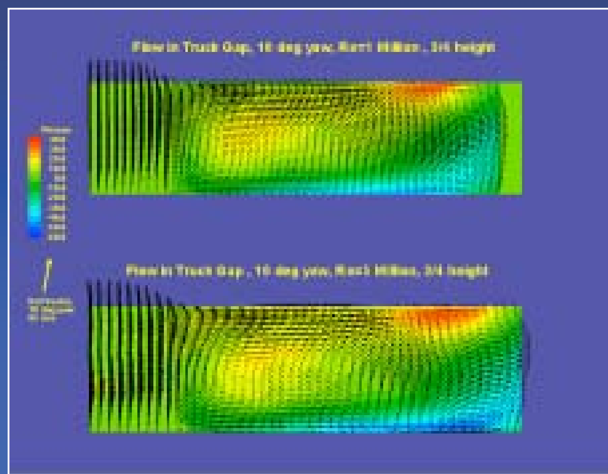


Ames Research Center

Comparison of 7x10 data and 12’ PWT data

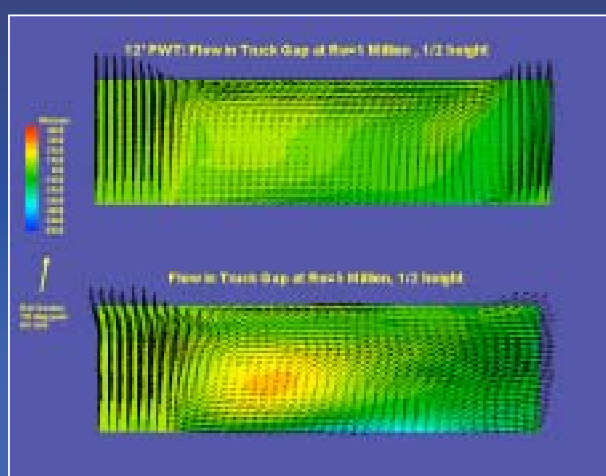


Effect of Reynolds Number at 1/4 height



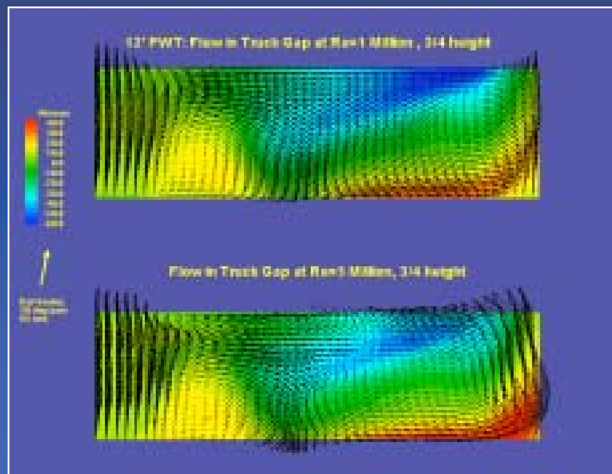
Ames Research Center

Effect of Reynolds Number at _ height



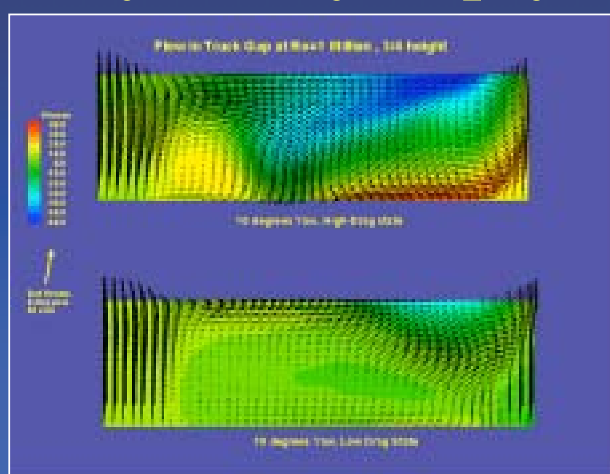
Ames Research Center

Effect of Reynolds Number at _ height

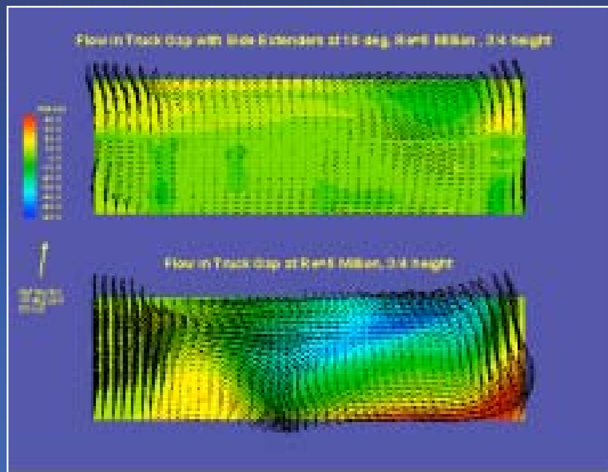


Ames Research Center

The High and Low Drag State at _ height



Effect of Side Extenders



In Conclusion

Gap data looks solid, High Re data may need further refinement

Effects of Reynolds noticeable

Thanks for your support, Sid, Jules and Rose
(oh, yeah, and Jim)

Reynolds Number Effects

- ***Minimal influence*** of Reynolds number on C_d for the 12’ tests => BUT ***big influence*** on the flow structure in the gap
- ***Edge radius*** effect on flow separation from the tractor
  - Need corner radius to be Re > 50K
- ***Optimization***
  - ***Don’t know*** the effect of Reynolds on the ***optimal flap angle***
  - ***Do know*** that the ***optimized side extender length*** changed with Reynolds number

Wind Tunnel Effects

- ***Absolute numbers*** are affected by flow quality
  - BUT the overall character of the ***drag remained the same***
  - Flowfields from the 7’ x 10’ and 12’ wind tunnels looked different

Future Directions

- Publishing data
- Underhood flow
- Underbody flow and splash and spray requires B.L.C.
- Brake cooling
- Coal cars
- Flatbed trucks
- What does industry need?

Overview of Computational Effort

Kambiz Salari

Lawrence Livermore National Laboratory

Heavy Vehicle Aerodynamic Drag Working Group Meeting
May 29-31, 2003

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Computational Approaches

- **Direct Numerical Simulation (DNS)**
  - **No turbulence modeling is required, all length scales are resolved**
  - **Prohibitively expensive at high Reynolds numbers**
- **Large Eddy Simulation (LES)**
  - **Turbulence modeling is required at sub-grid scale level**
  - **high Reynolds number simulations could be performed**
  - **There is an issue with wall boundary condition at high Reynolds numbers**
- **Reynolds Averaged Navier-Stokes (RANS)**
  - **Turbulence modeling is required for most of the relevant length scales**
  - **It is used for steady and unsteady simulations**
  - **Not as accurate as LES and DNS for massively unsteady separated flows**
  - **Routinely used in industry for modeling and simulations**
- **Hybrid RANS-LES Models**
  - **It is a relatively new approach**
  - **It is an engineering fix to provide wall boundary condition for LES type simulation**

Focus of Aero-Team Computational Effort

- Lawrence Livermore National Laboratory
  - Large Eddy Simulation
  - Steady and unsteady RANS
  - Hybrid RANS-LES methods
  - Validate computational model
- Sandia National Laboratories
  - Steady RANS
  - Hybrid RANS-LES methods
  - Validate computational model
- Argonne National Laboratory
  - Steady RANS
  - Using commercial codes
- Caltech
  - Vortex method, meshless approach

Questions about RANS Predictive Capability

- What are we looking for to predict?
  - Aerodynamic forces
    - Absolute
    - Changes
  - Steady flow behavior
  - Unsteady flow around the vehicle
  - Flow behavior around components
- What are the key issues that could influence RANS predictive capability?
  - Geometry
    - Sharpe edges
    - Smooth surfaces
  - Turbulence model
    - Flow separation and reattachment
    - Free shear layer
  - Wall treatment such as wall function
  - Grid resolution

What Do We Know about RANS Predictive Capability

- **Steady RANS**
  - **Inexpensive**
  - **Predictive capability**
    - **Wall bounded flows are reasonably predicated with no significant flow separation**
    - **Various turbulence models exists with different physical modeling of the turbulence in the flow. Turbulence models can significantly influence the predictive capability of RANS**
    - **The wake flow structure of bluff bodies are not captured correctly**
- **Unsteady RANS**
  - **More costly than RANS but still affordable**
  - **Predictive capability**
    - **It improves the prediction of unsteady flows by capturing unsteady flow structures such as periodic motion and wake undulation**
    - **Turbulence models are the same as the RANS**

Application of RANS to Heavy Vehicle

- **Meshing Techniques**
  - **Structure**
    - **Boundary fitted**
      - **Multi-block**
      - **Overset**
    - **Cartesian**
  - **Unstructured**
    - **Boundary fitted**
      - **Overset**
    - **Cartesian**
- **Turbulence models**
  - **Spalart-Allmaras *(SA)***
  - **Wilcox *k-w* (1988)**
  - **Menter *SST***
  - **High Reynolds number *k-e* with wall function**
  - **Renormalization group (RNG) *k-e***
  - **Hassan k-z**
  - **Durbin V2f**

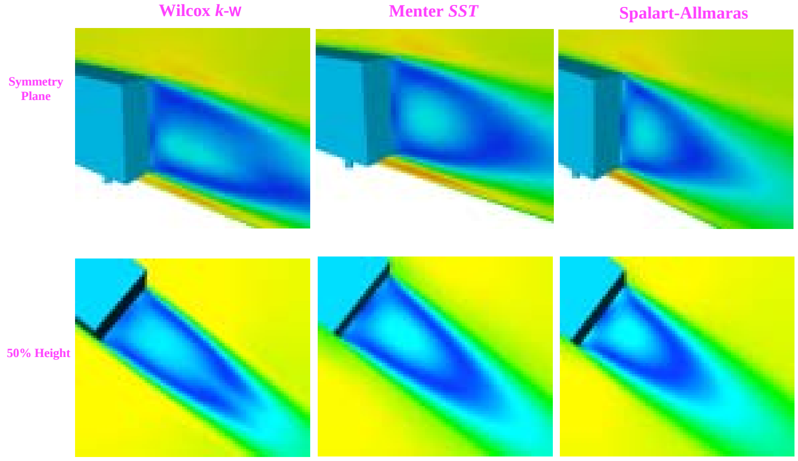
RANS Simulations of Heavy Vehicle

- **Lawrence Livermore National Laboratory**
  - Research/commercial code OVERFLOW
  - Overset structured grid
  - Steady and unsteady RANS
  - GTS/GCM geometry
- **Sandia National Laboratories**
  - Research code SACCARA
  - Multi-block structured grid
  - Steady RANS
  - GTS geometry
- **Argonne National Laboratory**
  - Commercial code Star-CD
  - Cartesian unstructured grid
  - Steady RANS
  - GCM geometry

Full Vehicle Simulation using RANS

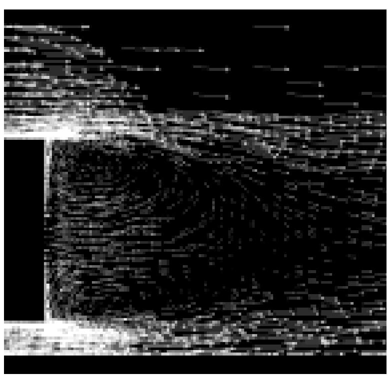
- **GTS model in NASA 7'x10' wind tunnel**
  - **0° and 10° yaw**
  - **Turbulence models**
    - **Spalart-Allmaras (*SA*)**
    - **Wilcox *k-w* (1988)**
    - **Menter *SST***
  - **Steady RANS solution**
    - **Two grids: 3.7M and 12.2M elements**

OVERFLOW Computational Results

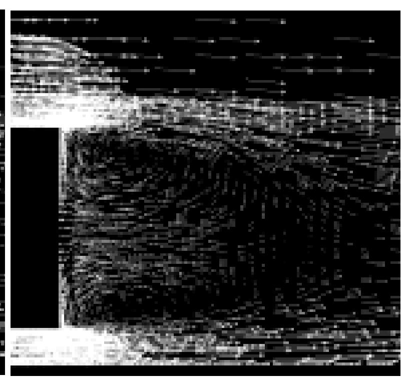


OVERFLOW Computational Results, …

Wake flow structure, Menter *SST*, 0° yaw, Symmetry plane



Coarse mesh, 3.7 M Elements



Fine mesh, 12.2 M Elements

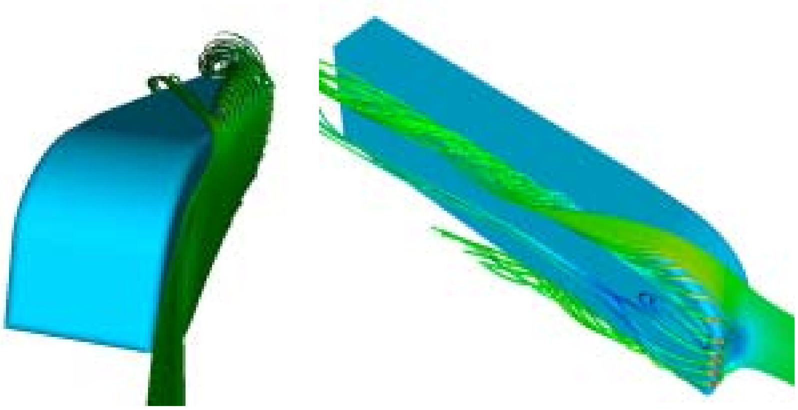
Aerodynamic forces, 0° yaw

Drag	Viscous	Pressure	Total
Wilcox *k*-W, coarse grid	0.103	0.188	0.290
Wilcox *k*-W, fine grid	0.101	0.176	0.277
Menter SST, coarse grid	0.091	0.273	0.364
Menter SST, fine grid	0.092	0.258	0.350
Spalart-Allmaras, fine grid	0.096	0.294	0.390
NASA Experiment, $C_{D,W}$*			0.249
NASA Experiment, $C_{D,R}$*			0.263

* Subscript W refers to the static pressure measured on the test-section tunnel wall and subscript R refers to the static pressure measured upstream of the test section

OVERFLOW Computational Results, 10° yaw

Particle traces are colored by velocity magnitude

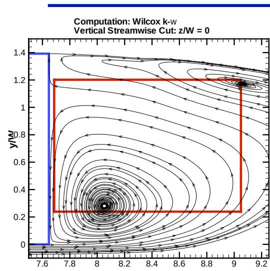


Wilcox *k*-W turbulence model

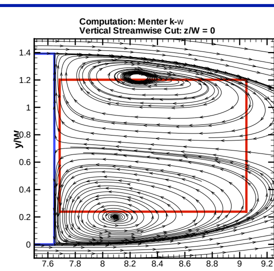
Aerodynamic forces, 10° yaw

	Lift	Drag	Side
Wilcox *k*-W, fine grid	-0.004	0.581	1.127
Menter SST, coarse grid	0.006	0.651	1.129
Menter SST, fine grid	-0.010	0.664	1.137
NASA Experiment, $C_{D,W}$	0.021	0.292	1.253
NASA Experiment, $C_{D,R}$	0.022	0.312	1.338

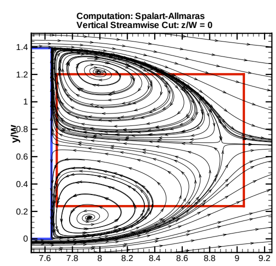
Sandia: SACCARA Trailer Wake Results



Menter (coarse), CD = 0.47



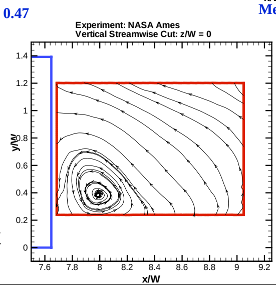
Menter (fine), CD = 0.30



Spalart (fine), CD = 0.41

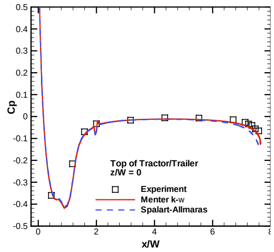
CD = 0.25

Experiment

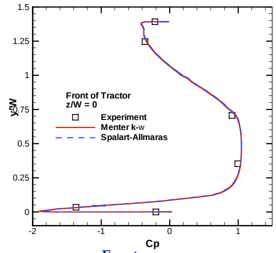


Coarse mesh: 2.5 mill. cells
Fine mesh: 20 mill. cells

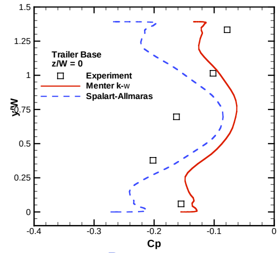
Sandia: Surface Pressures



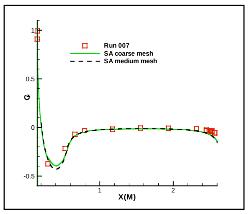
Top



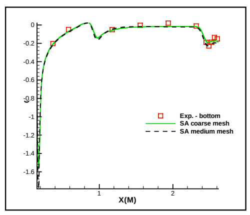
Front



Base



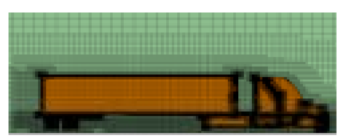
Top



Bottom

Argonne: GCM Analyses with Star-CD

- **Comparison of Basic Steady RANS models using Star-CD setup recommended by Adapco**
  - **Error in predicted Drag Coefficient**
    - **High Reynolds number k-epsilon model : 0.47 %**
    - **Renormalization group (RNG) k-epsilon model: 1.80 %**
    - **k-omega SST hybrid k-epsilon model: 0.44 %**
  - **Better agreement than expected using basic steady RANS turbulence models**
- **Shifted focus from comparison of numerous turbulence models and modeling approaches to thorough verification of results of initial study**
  - **Sensitivity of solution to mesh structure**
  - **Sensitivity of solution to domain size**
    - **Dimensions of the virtual wind tunnel**
  - **Half model vs. full model**
  - **Scalability**

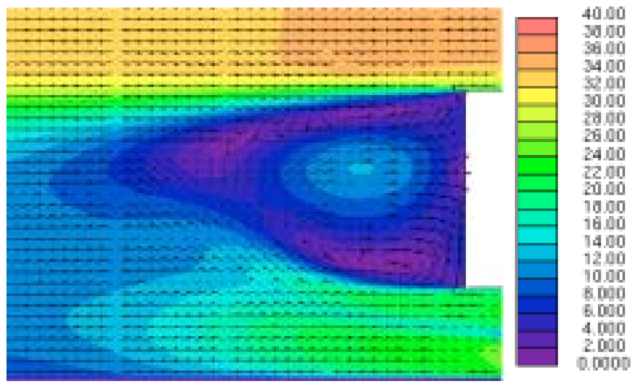


Near vehicle region of a typical computational mesh

Typical centerline velocity profile

Argonne: Star-CD Result

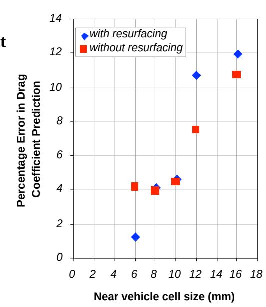
half-vehicle GCM simulation using the k-omega SST model



Vertical Plane at Vehicle Centerline Showing
Velocity Distribution in Wake

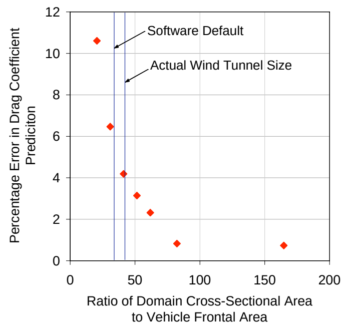
Argonne: Mesh Sensitivity

- **Near vehicle cell size**
  - Standard cell size within near-vehicle region
  - ~ _ vehicle width from all surfaces
  - Effects of near vehicle cell size shown by red data points at right
    - All cases use same starting surface with a base resolution of 8 mm
    - Refinement of computational mesh beyond surface resolution does not appear to improve prediction
- **Starting surface refinement**
  - Effects of matching the resolution of the trimming surface used to the near vehicle cell size by "wrapping" surface shown by blue data points
- **Near wall refinement**
  - Result of successive refinement of base near-vehicle cells based on local geometry
  - Refined before vehicle surface is used to trim mesh surfaces
  - For a near vehicle cell size of 8.0 mm, increasing the near wall resolution from 0.5mm to 1.0mm increases error in drag coefficient prediction from 0.47% to 4.1%



Argonne: Other Sensitivities

- **Full-vehicle versus half-vehicle**
  - **Use of full-vehicle models versus half-vehicle models appears to yield modest improvement in predicted drag coefficients**
- **Domain Size**
  - **Effects of domain size on predicted drag coefficient shown at right**
    - **Using wind tunnel geometry may not improve accuracy of prediction compared with CORRECTED wind tunnel data**
  - **Case uses 8.0 mm near vehicle cell size and 1.0 mm near wall cell size limit**
  - **Little change in number of computational cells or in computational time between cases**
  - **Considerable improvement in prediction if larger domain is used**



Conclusions

- **RANS/URANS is a viable approach to model flow around heavy vehicle. However, it fails to correctly predict the flow structure in the wake**
- **The user of RANS approach has to recognize the limitation of the turbulence models offered in the code and use it accordingly**
- **Lack of proper grid convergence in a predictive simulation is a problem and can lead to a false confidence of result**
- **Grid generation still is the most time consuming part of these simulations and automation, such as Star-CD Cartesian grid approach is quite useful. However, the best approach is to eliminate the volume mesh from the simulation such as vortex method**

Computational Summary

Modeling methods

- DNS
- LES
- Hybrid Methods
- Unsteady RANS
- Steady RANS
  - With and without wall functions

Structured grid vs unstructured grid vs. no grid

Four efforts in computational modeling

- LLNL, SNL, ANL and Caltech

Results

- Drag prediction
  - Heavily model dependent
    - Have to know the answer to get the answer ?
  - RANS models seem to do well
    - Separated regions?
    - Different models give very different results
- Local flow predictions
  - Disconnect between drag and local flow prediction
  - Time dependence in solution needed for comparison to time averaged data

Issues

- How do you make comparisons?
  - Between methods
    - Steady vs. time averaged
  - Between prediction and experiments
- Delta's versus absolute?
  - Interest in looking at boat tails or flaps
- Base pressure prediction?
- Need to identify needs of OEM's

‘Working Group Meeting’

Consortium for Aerodynamic Drag of Heavy Vehicles

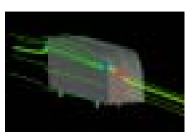
Department of Energy, Office of FreedomCAR & Vehicle Technologies

May 30, 2003

Rose McCallen, Kambiz Salari, Jason Ortega	University of California Lawrence Livermore National Laboratory
Chris Roy, Larry DeChant, Basil Hassan	Sandia National Laboratories
James Ross, Dale Satran, J.T. Heineck, Steve Walker	National Aeronautics & Space Administration
Fred Browand, Mustapha Hammache, Tsun-Ya Hsu, Diego Arcas	USC UNIVERSITY OF SOUTHERN CALIFORNIA
Anthony Leonard, Mike Rubel, Philippe Chatelain	Caltech California Institute of Technology
Robert Englar	Georgia Tech Research Institute
David Pointer, Tanju Sofu	ARGONNE NATIONAL LABORATORY

*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

GOOD SCIENCE

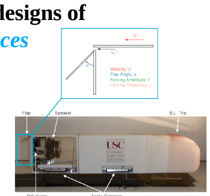


LLNL, SNL, ANL, Caltech
High quality numerical *computations*
<u>Guidance</u> on computational tools

NASA, USC
Data base of high quality wind tunnel *experiments*

USC, NASA, LLNL, SNL
Comparisons and analyses
<u>Insight</u> into flow phenomena

USC, GTRI, LLNL
Concepts and designs of aero *devices*



TEAM, Industry
Information exchange

PACCAR Inc
FREIGHTLINER
VOLVO

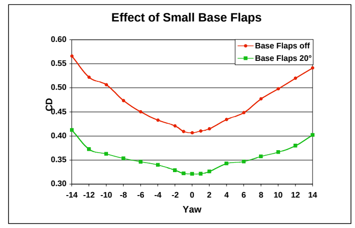
INDUSTRY SUPPORT

NEAR-TERM BENEFIT

The FY03 deliverables provide near-term guidance to industry.

Guidance for drag reduction devices

- 20-25% drag reduction with base flaps (silent Mozart)
- "Gap Stabilizer"
- Base winglets and underbody shields



Guidance for experiments

- Reynolds number and scaling effects

Guidance for computations

- Steady vs. Unsteady RANS
- Choice of RANS model
- Grid refinement

Teaming with industry

DOE RFP	Full-scale testing (Freightliner)
	Splash & Spray (Michelin, Freightliner)
CRADA	Commercial tools (PACCAR)

Recognition from UEF Conference → Industry Consortium !

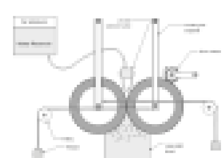
FY04 plans push into new areas with big impact.

Mozart hits the road !

- Truck friendly base flaps → Fleet trials

Underbody is coming out !

- Discovery experiments test "The V-Shield"
- Water channel experiments for moving plane effects

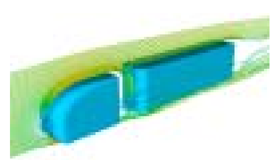


Will be Rolling, Splashing & Spraying !

- Moving plane wind tunnel, new "tire rig" tests

Computations push the envelope !

- Validation using 12' PWT data ... Full-scale Re !
- Vortex methods applied to 3D, complex geometry
- LES/RANS with GCM (aka SLRT), finalized for GTS



Publish, publish, publish !

- Guidance, insight → drag reducing design

NEW collaborative efforts

CRADAs?	Fleet trials (International, PATH)
	Splash & Spray (Michelin, USC)

FY04 proposed budget provides an 11% reduction below last year's baseline total.

Criteria

- **Activities are complimentary**
- **Consideration of critical activities → biggest bang for the bucks**
- **SOWs** **Prioritized tasks**
  - **Additions/reductions for a 20% budget increase/reduction**

Proposed baseline budget

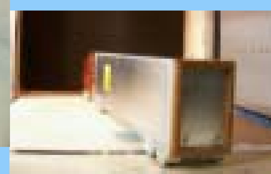
NASA	**$ 265K**
USC	**200K**
Caltech	**135K**
SNL	**225K**
Management (LLNL)	**<u>150K</u>**
Total	**$ 1,425K**

Pneumatic Heavy Vehicle Aerodynamic Drag Reduction, Safety Enhancement, and Performance Improvement, An Update

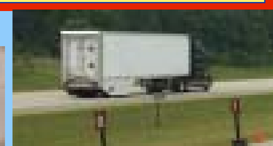
~LLNL Aerodynamic Drag of Heavy Vehicles Meeting, 5/29&30/03~

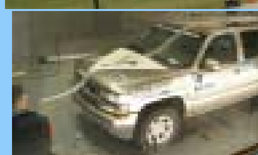
by Robert J. Englar, Georgia Tech Research Institute

Application of Advanced Pneumatic Aircraft Technology....



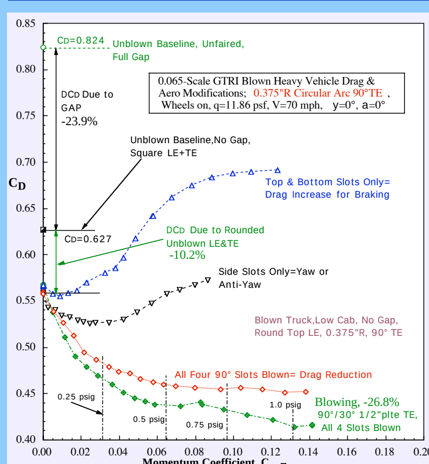
...Through Analytical & Experimental Development ...





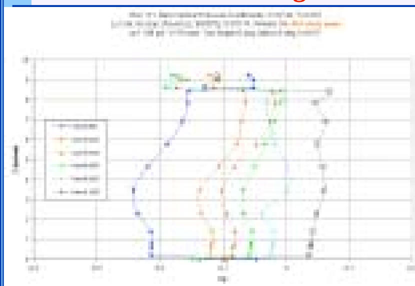
..To Proof-of-Concept Full-Scale Tests

Background: Aero Development at GTRI Showed 50%(or more)Drag Reduction+Force/Moment Augment. from Blowing of Various Slots

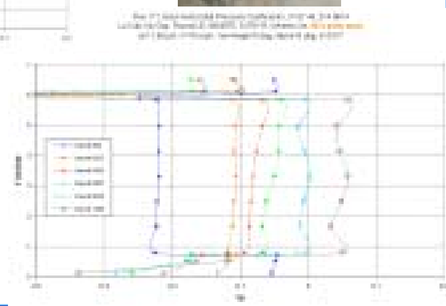


4 Blown Slots & Jet Turning on Rear Doors of Wind-Tunnel Model

The Effects of Blowing on Increasing Base Pressure, 90/30°TE

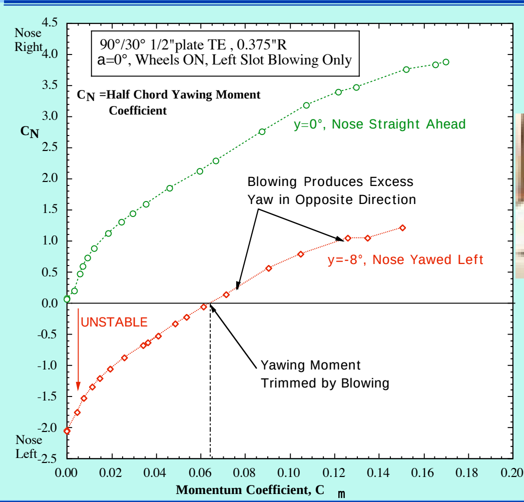


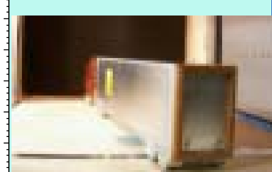
Vertical Mid Base



Horizontal Mid Base

Directional Control Capability Provided by Blowing of Left Side Slot Only





Additional Gain from Side Blowing:
Reduced C_D due to Yaw

On-the-Road Tuning Tests: Jet Turning Entraining the Flowfield and Reducing Vehicle Drag

Rear View with Jets Blowing

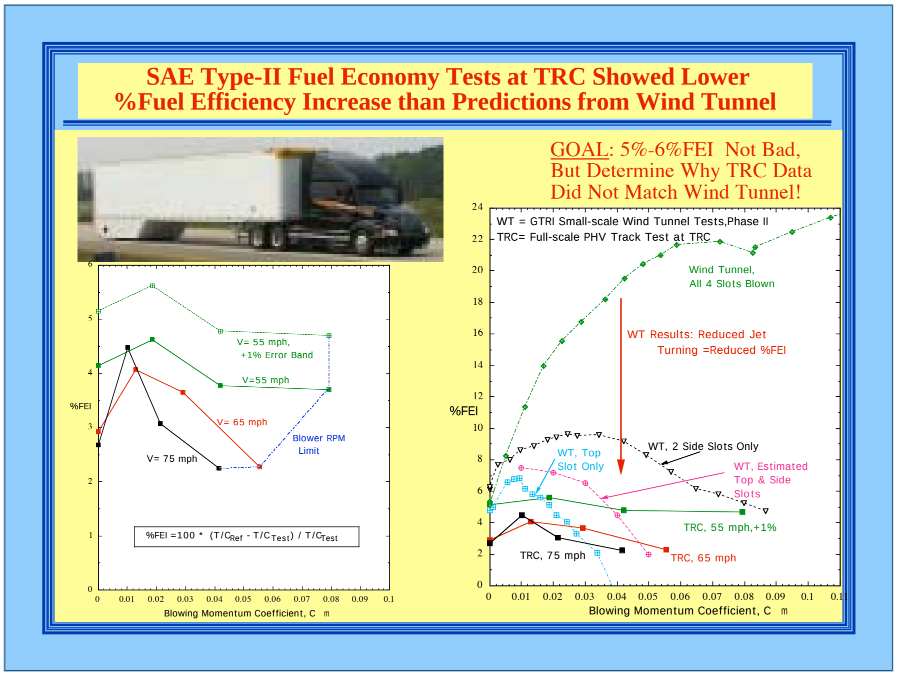
Close-up of Tufts Showing Jet Turning

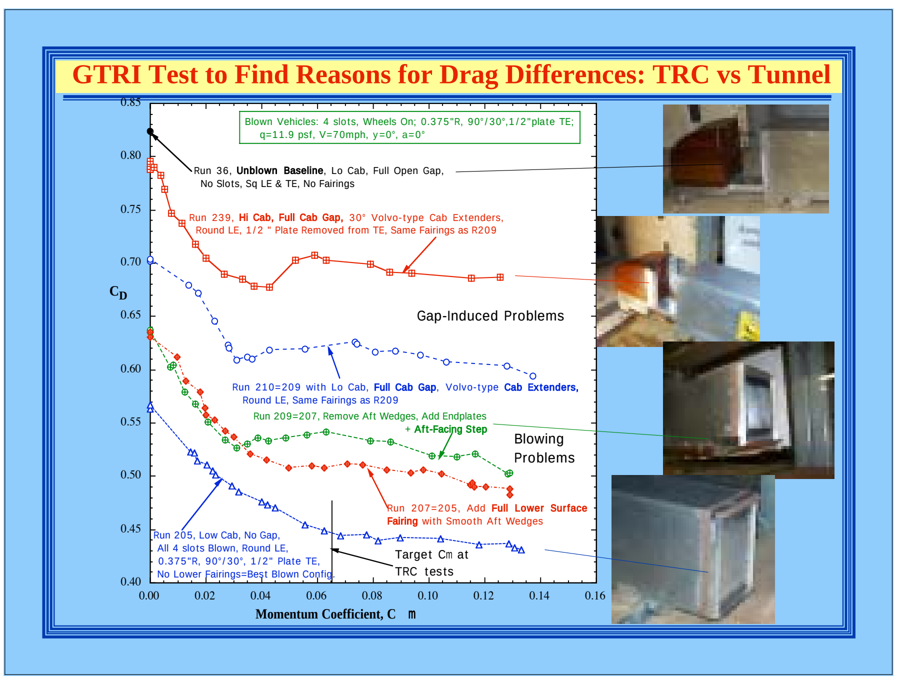
Tuning Test Results (V=65 mph), Comparison to GTRI Wind Tunnel Results, and Conclusions

Configuration	WindTunnel C_D	% C_D Change	% Equiv. GPM Reduction	Road Test Run No.	% GPM Reduction	% Equiv. C_D Change	% MPG Increase
Baseline, No Gap, Sq. LE & TE	0.627	0	0.0	13 (Gap)	0.00	0.00	0
Unblown PHV, Cmu=0	0.57	-9.1	-4.6	9	-10.21	-20.42	11.37
PHV,4 Slots Cmu=0.05	0.44	-29.8	-14.9	5	-13.27	-26.54	15.30

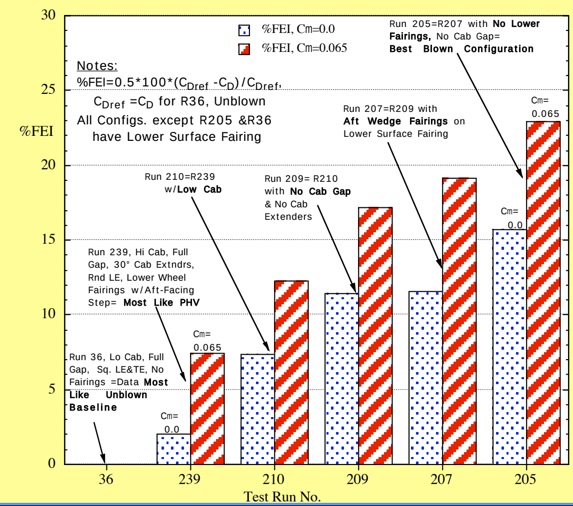
CONCLUSIONS:

- Limited Tuning Runs (Unofficial) confirmed up to **15.3% increase in MPG,** or about **26.5% reduction in C_D**, due to blown PHV configuration, with **Lower Aero Fairing installed, but OPEN between Wheels**
- Conducted 2nd Tuning Test (TT2) **Lower Aero Fairing CLOSED at LE & TE - Aft step formed**


SAE Type-II Fuel Economy Tests at TRC Showed Lower %Fuel Efficiency Increase than Predictions from Wind Tunnel
GOAL: 5%-6%FEI Not Bad, But Determine Why TRC Data Did Not Match Wind Tunnel!
V= 55 mph, +1% Error Band
V=55 mph
V= 65 mph
V= 75 mph
Blower RPM Limit
%FEI
%FEI =100 * (T/CRef - T/CTest) / T/CTest
Blowing Momentum Coefficient, Cm
WT = GTRI Small-scale Wind Tunnel Tests,Phase II
TRC= Full-scale PHV Track Test at TRC
Wind Tunnel, All 4 Slots Blown
WT Results: Reduced Jet Turning =Reduced %FEI
WT, 2 Side Slots Only
WT, Top Slot Only
WT, Estimated Top & Side Slots
TRC, 55 mph,+1%
TRC, 75 mph
TRC, 65 mph
Blowing Momentum Coefficient, Cm


GTRI Test to Find Reasons for Drag Differences: TRC vs Tunnel
Blown Vehicles: 4 slots, Wheels On; 0.375"R, 90°/30°,1/2"plate TE; q=11.9 psf, V=70mph, y=0°, a=0°
Run 36, Unblown Baseline, Lo Cab, Full Open Gap, No Slots, Sq LE & TE, No Fairings
Run 239, Hi Cab, Full Cab Gap, 30° Volvo-type Cab Extenders, Round LE, 1/2 " Plate Removed from TE, Same Fairings as R209
Gap-Induced Problems
Run 210=209 with Lo Cab, Full Cab Gap, Volvo-type Cab Extenders, Round LE, Same Fairings as R209
Run 209=207, Remove Aft Wedges, Add Endplates + Aft-Facing Step
Blowing Problems
Run 207=205, Add Full Lower Surface Fairing with Smooth Aft Wedges
Run 205, Low Cab, No Gap, All 4 slots Blown, Round LE, 0.375"R, 90°/30°, 1/2" Plate TE, No Lower Fairings=Best Blown Config.
Target Cm at TRC tests
CD
Momentum Coefficient, Cm

Predicted Fuel Efficiency Increase after PHV Road Test Vehicle Converted To Best Model Configuration (Run 205)



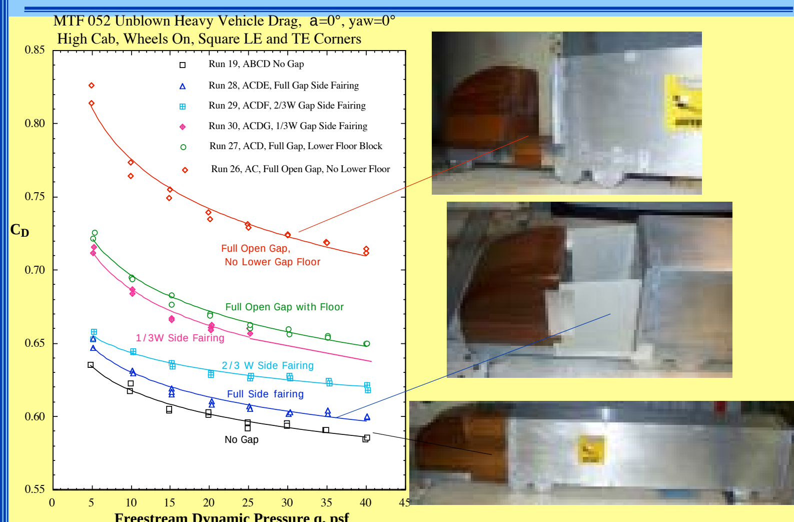
Run 205 has 23 %FEI $\approx$ 46% C_D reduction compared to Run 36

Notes:

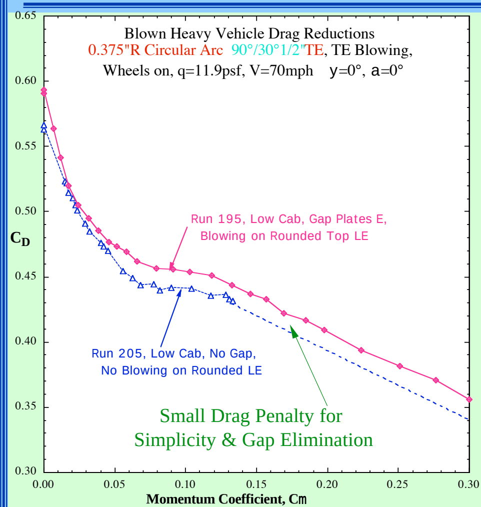
Run 205 is best blown PHV configuration

Run 36 is most like standard baseline HV

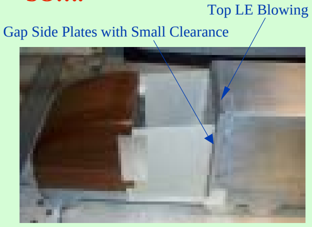
The Seriousness of the Cab Gap Problem



A Practical Alternative to the Cab Gap Problem



Cab "Non-Gap" (Filled) is Effective, but Not Practical, SO….



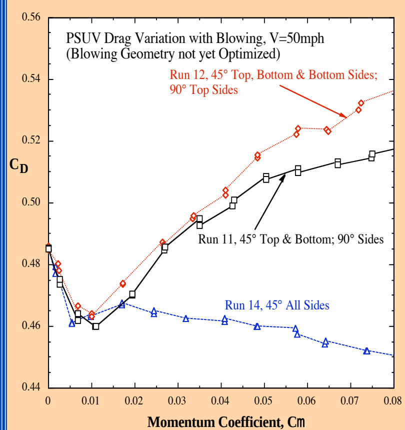
...Substitute Gap Side Plates and Top LE Blowing

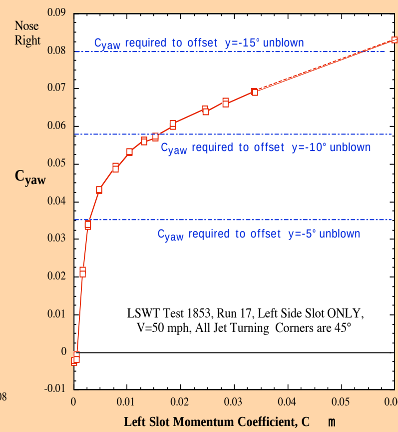
Full-Scale Tunnel Tests of Unblown SUV to Locate Flow Separation for Blowing Slot Location of Pneumatic SUV

Smoke Flow over Unblown SUV

Separated Flow over Aft Door of SUV

Pneumatic Capabilities of Blown SUV Confirmed in WT Test





Drag Reduction or Aero Braking,
Systems Interchangeable

Directional Stability,
No Moving Parts

CONCLUSIONS: Pneumatic Aerodynamic Concepts Now Demonstrated Full-Scale on PHV and PSUV

- **Blowing Confirmed on Full-Scale PHV Tests at TRC, but showed less Drag Reduction than anticipated from Tunnel Tests**
- **23% to 24% Fuel Efficiency Improvement still Possible Based on 46-48% C_D Reduction if PHV Test Vehicle Can Approach Wind Tunnel Model Characteristics**
- **Pneumatic Yaw Stability & Aero Braking Capabilities Confirmed**
- **Pneumatic Full-scale WT Tests Showed Similar Blown Capabilities for SUV**
- **Need to Understand Magnitude of Flow Entrainment vs Aft Pressure Recovery vs Corner Effects and their Interactions w.r.t. Effective Pneumatic Performance ~Need to Evaluate Any Degrading Elements, then Pose Positive Solutions**
- **Improvements Underway!!**

Planned GTRI FY03 Program

- Task 1- Modify & WT Evaluate Improved PHV Configurations
  SLRT Tractor, Std. Trailer Floor Height, Variable Gap & Extenders,
  No Lower Fairings, Improved Pneumatics
- Task 2- Assist NASA ARC in High Re Testing of PHV Config.
  - Plenums, Slots and Turning Surfaces on 1/8 GCM Trailer
  - Flow controls and instrumentation
  - Conduct High Reynolds Number Tests with Blowing Modifications
- Task 3- Redesign & Modify for Full-Scale PHV Road Test
- Task 4- Conduct Preliminary Road Tests of Modified PHV
- Task 5- SAE Type-II Fuel Economy Tests at TRC, Phase II (FY03 Option)
  (Move to FY04)

Tasks 1&2, Tasks 3&4, and Task 5 to be funded in separate increments

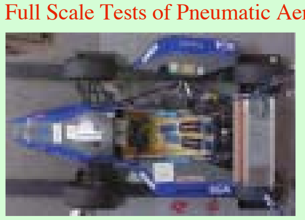
Contract was amended and GTRI was notified on **May 27, 2003**, so we are just now starting these FY03 Tasks 1 and 2 (approved by DOE HQ in Sept 2002)

Tasks 3 & 4 of FY03 may be added in June 2003 (says Oakland contract office)

Planned GTRI FY04 Program

- Task 6- Testing of 1/8 Scale PHV Model in NASA Ames 12' Wind Tunnel
- Task 7- Full Scale Testing of PHV Refinements

- Task 8- Full Scale Tests of Pneumatic Aerodynamic Heat Exchanger



USC Present Progress:
Next 4 Months

Write-up forces at large yaw: *Browand, Hsu & Satran or Heineck*

- Hopefully combine with NASA results

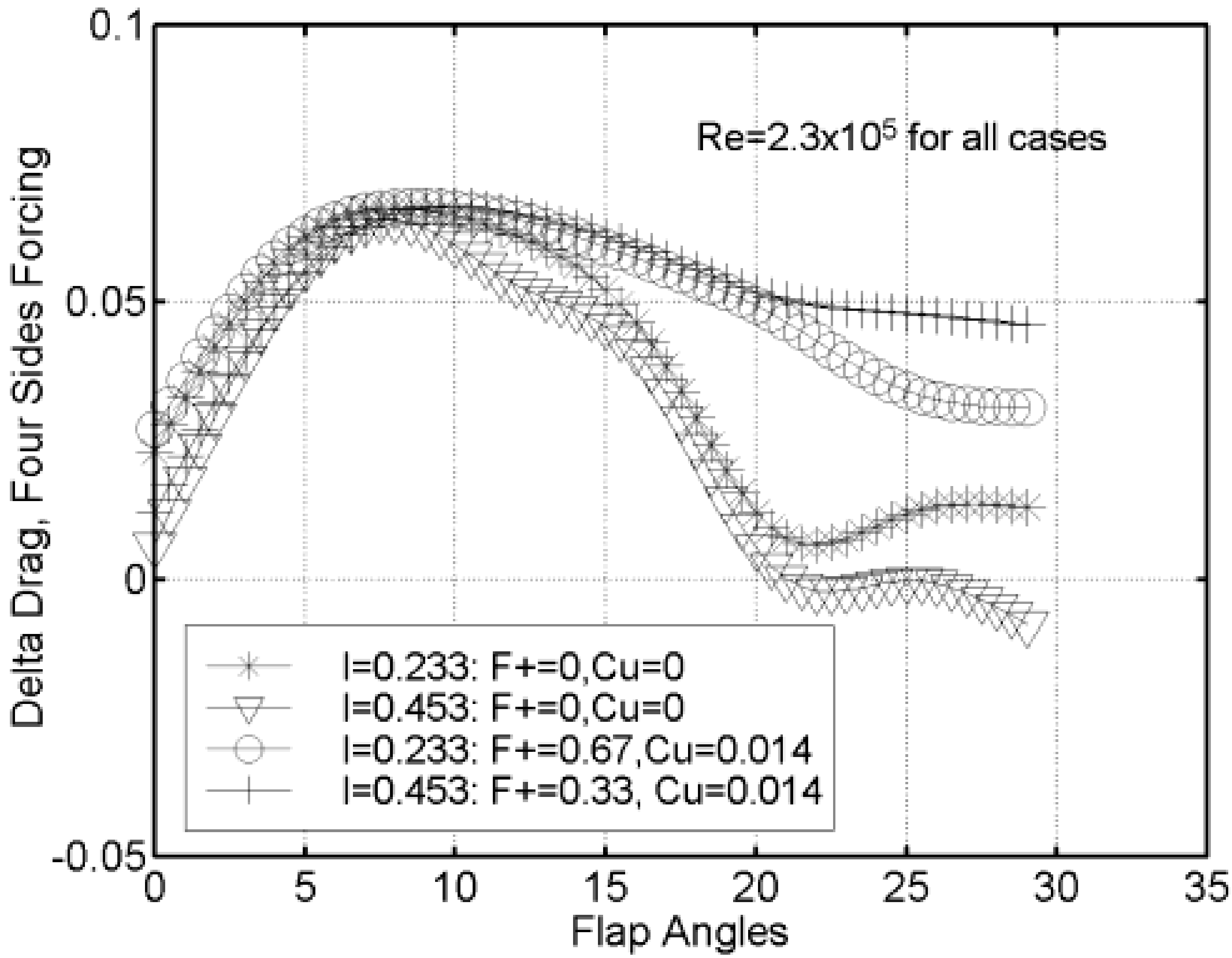
• Write-up gap flow results: *Arcas, Hammache & Browand*

• Submit SAE paper: Limits of drag savings for two close-following trucks: *Browand & Hammache*

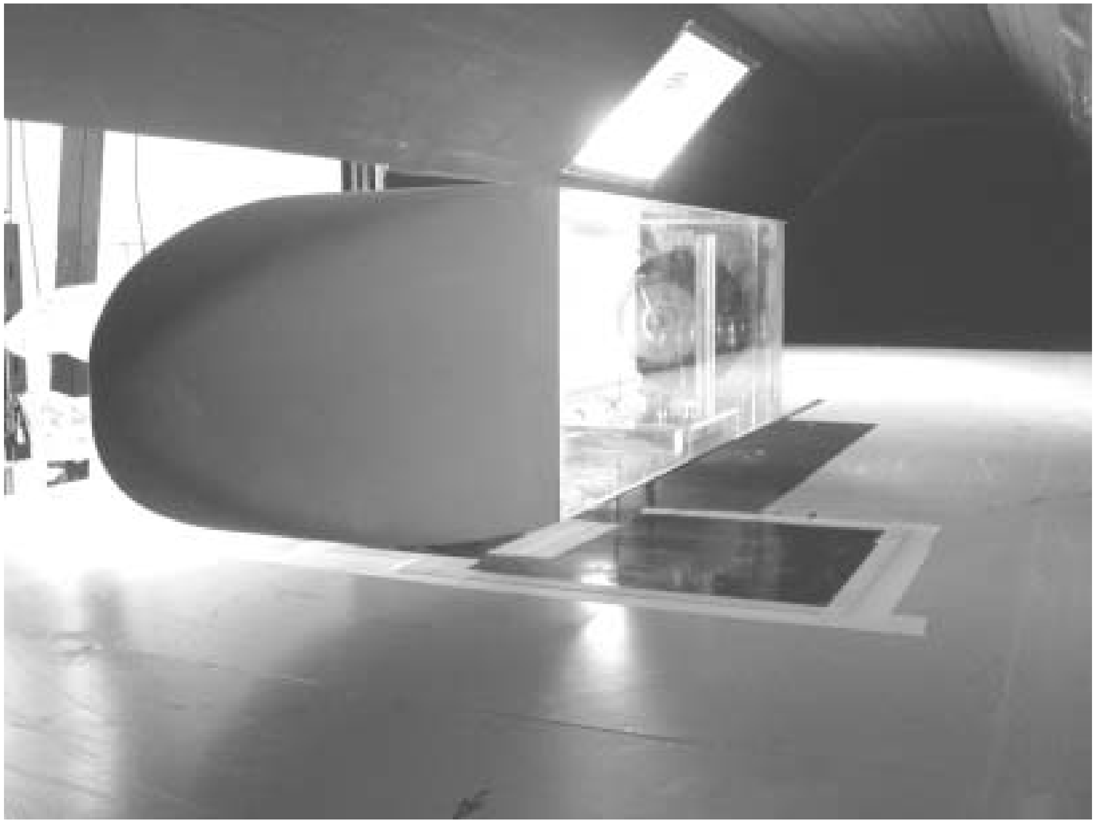
• Base flaps with forcing: *Hammache & Hsu*

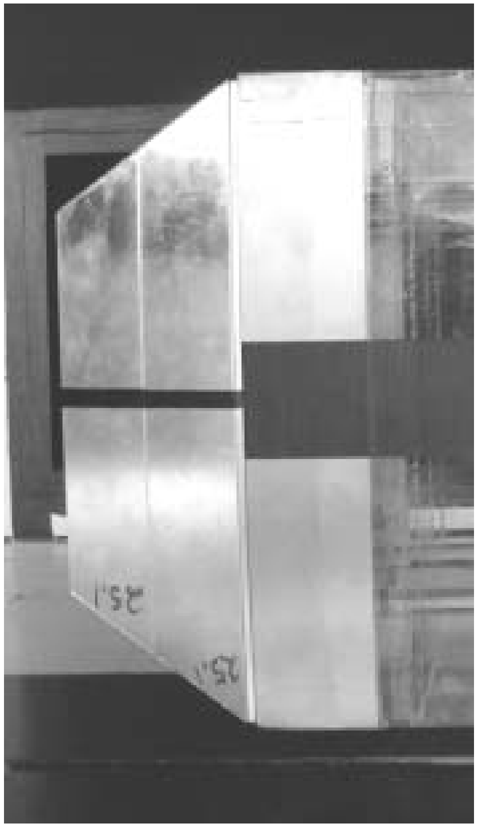
- Measure drag savings at increased levels of forcing
- Perform PIV over flaps

Effect on Drag Reduction of Base Flaps with Oscillatory Forcing

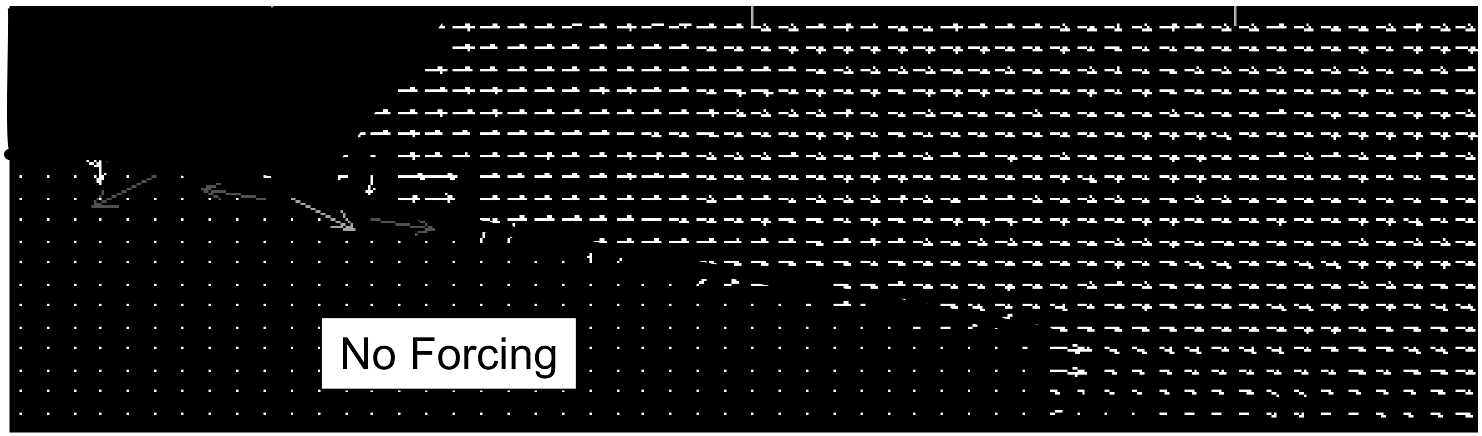


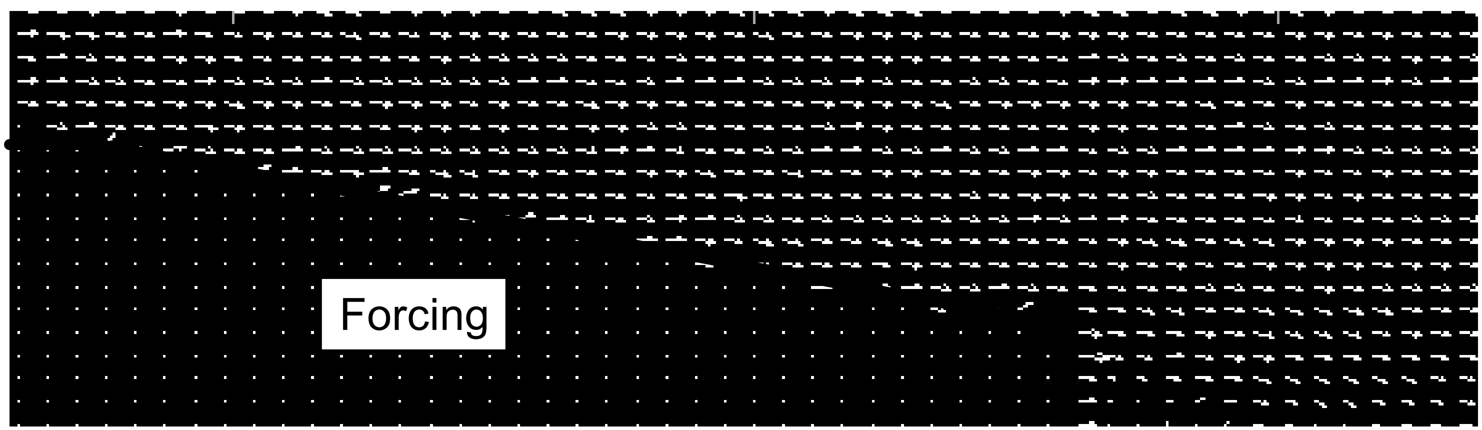
Drag Reduction Devices, USC Tests





Preliminary DPIV over Flaps





USC Statement of Work FY ’04
(FY ’04-’06)

- Base flaps at full-scale (field test)

- Underbody aerodynamics / Aerodynamics of rolling wheels
    - Water uptake/spray formation from rolling wheels
    - The moving ground plane wind tunnel

Implementation of Base Flaps in over the Road Trials

Anticipate finishing laboratory studies of the drag-reducing possibilities for base flaps or the base flaps with the addition of oscillatory forcing. The results of the NASA model tests at full-scale Reynolds numbers have demonstrated that base flaps are, in themselves, a sufficient performance improvement to warrant an over-the-road trial.

- Interest trailer manufacturer to provide design input for base flap construction

- Interest OEM to do testing

- Contract to California PATH to make part of their 3-truck demonstration platoon

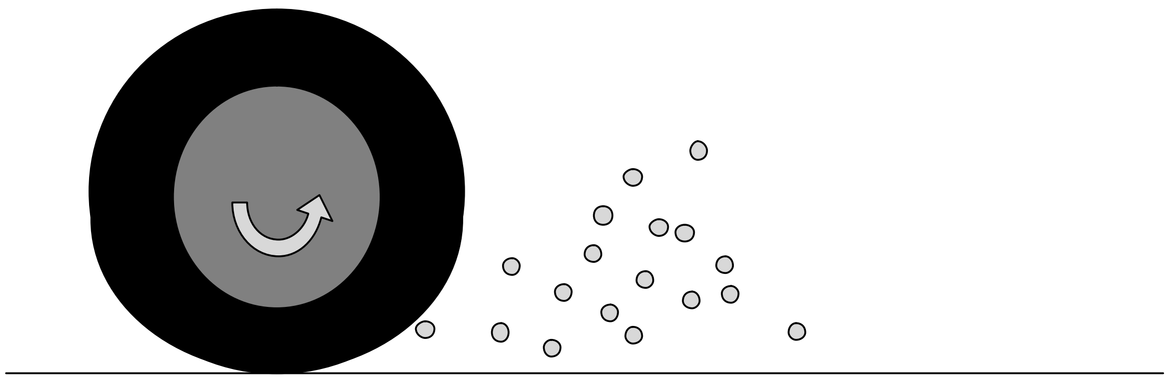
Water Uptake and Spray Formation from Rolling Wheels

Full-scale spray tests provide information on the movement of small droplets in the flow surrounding the wheel and the truck, but not much information about the *initial* droplet formation. Ideally one would like to study droplet formation under controlled conditions in a wind tunnel having a moving ground plane. This is not possible in our wind tunnel since we cannot introduce water onto the moving ground plane. To a first order of approximation, it can be argued that the *initial formation* of droplets depends strongly on the presence of the moving road surface and the velocity and acceleration of the tire (viewed from a coordinate system fixed to the vehicle), and depends to a lesser extent on the air flow about the wheel and tire.

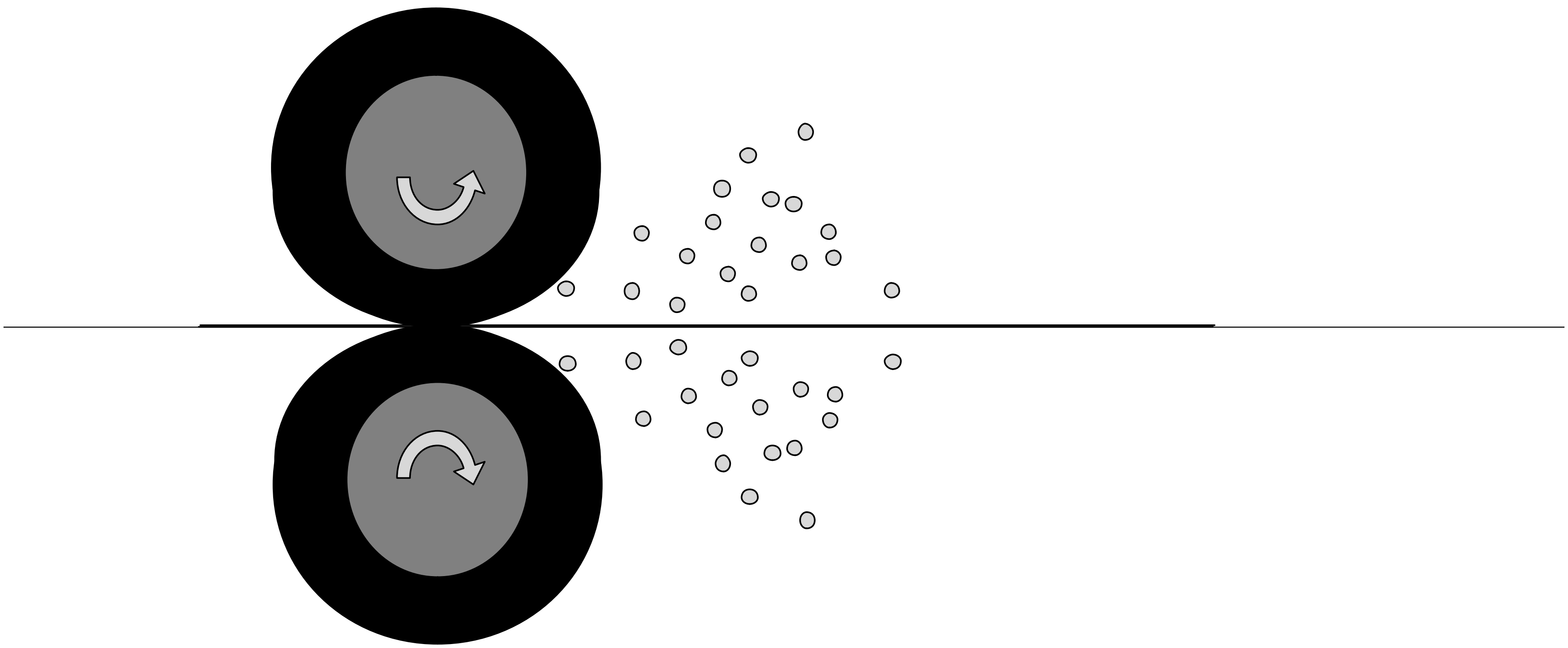
•<u>Construct test apparatus to measure primary water droplets formed in the wake of rolling tires.</u>

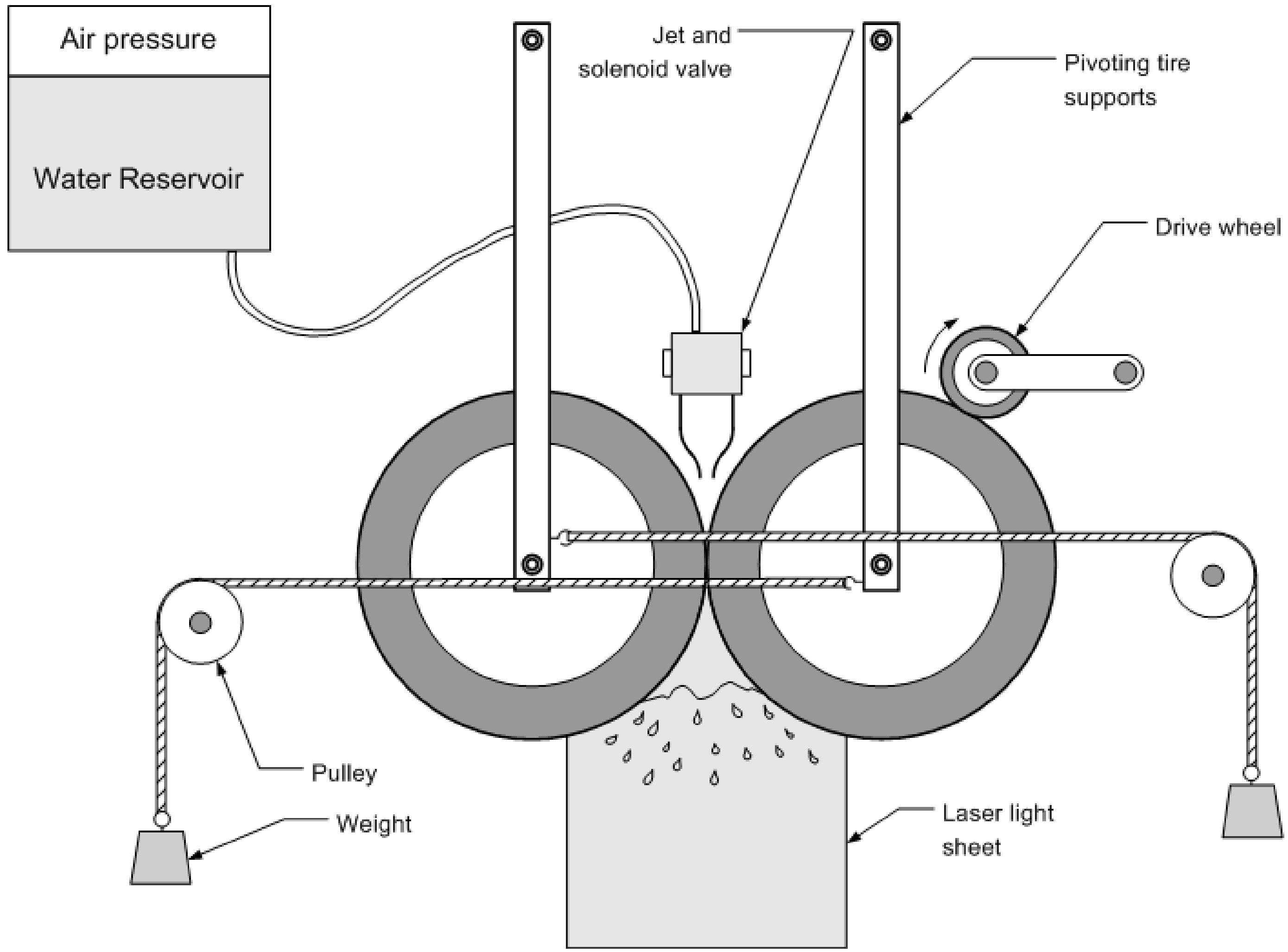
•<u>Investigate various tread geometries and tread patterns to understand their function in water uptake and spray formation.</u> <u>Suggest possible alternative tread patterns that may hold advantage in minimizing spray formation</u>.

Splash and Spray



Splash and Spray





The laser pulse duration is of the order of 5 nanoseconds and the time between pulse pairs is adjustable. Two separate images are recorded by a specially designed and buffered digital camera. Droplet sizes and velocities can be determined from these image pairs.

The Moving Ground Plane Wind Tunnel

Will help provide information on the aerodynamic drag of rolling wheels, and map the flow field in the vicinity of the wheels by means of DPIV. Experimental data can be compared with numerical solutions for flow about rolling wheels. Typical Reynolds numbers for these tests, ReD ˜ 350,000-400,000 (based upon wheel diameter)

- Improve belt feedback control mechanism to insure belt speed and wind tunnel speed remain in fixed ratio 1:1.

- Construct half-plane model of a simplified tractor-trailer geometry, mounted on the wall of the MGPWT.

- Make measurements of aerodynamic forces on the axle and rolling wheel, and make comparisons of the drag of dual-tires and wide-singles.

- Make *preliminary quantitative* comparisons of the differences in the flow fields in the vicinity of a dual-tire and a wide-single.

USC Statement of Work FY ’04
(FY ’04-’06)

- Base flaps at full-scale (field test)

- Underbody aerodynamics / Aerodynamics of rolling wheels
    - Water uptake/spray formation from rolling wheels
    - The moving ground plane wind tunnel

Flow Visualization Measurements of the Modified GTS Geometry

Jason Ortega
Kambiz Salari
Rose McCallen

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

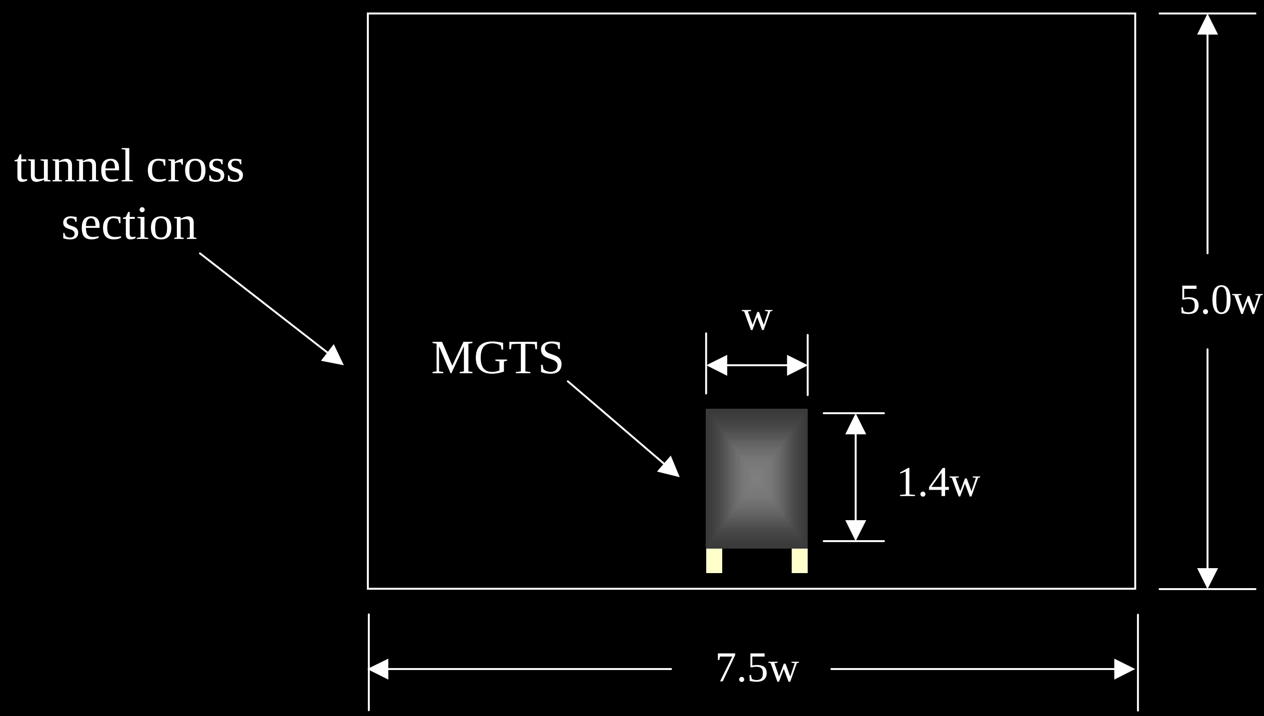
Overview

- Experimental goals
- Experimental setup and technique
- Flow visualization measurements
- Conclusions
- Future work

Experimental Goals

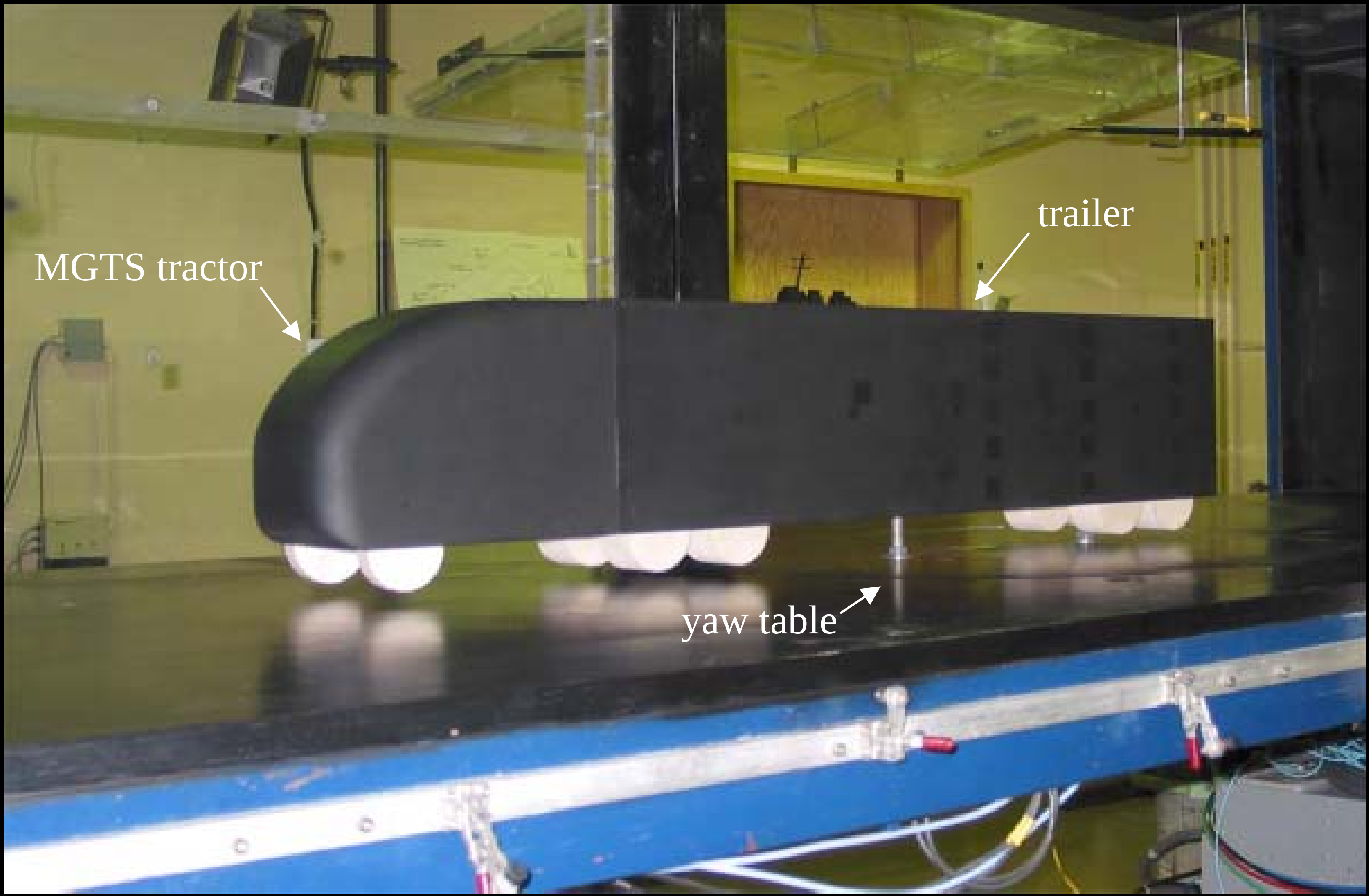
- ***Design*** and ***construct*** a 1/16th scale tractor/trailer model for ***wind tunnel testing***
- Provide a relatively ***simple*** and ***inexpensive*** means for testing the effectiveness of various ***add-on drag reduction concepts***
- ***Better understand*** the fluid mechanics of the complex, 3-D flow field about the tractor/trailer

Experimental Setup

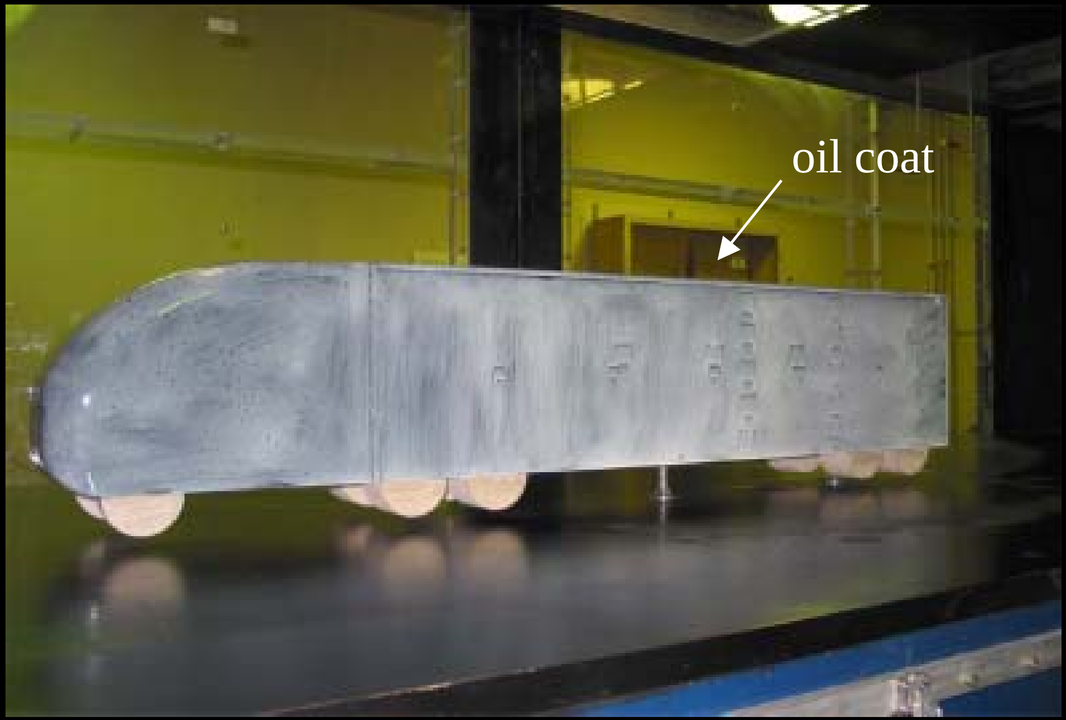


- NASA Ames FML 48” Δ 32” wind tunnel
- U_o = 140 fps
- Re_w = 461,000
- Yaw angle range of $\partial 14^o$
- Trailer outfitted with 39 ***pressure taps***
- ***Force*** and ***moment*** measurements made with force balance

MGTS Model

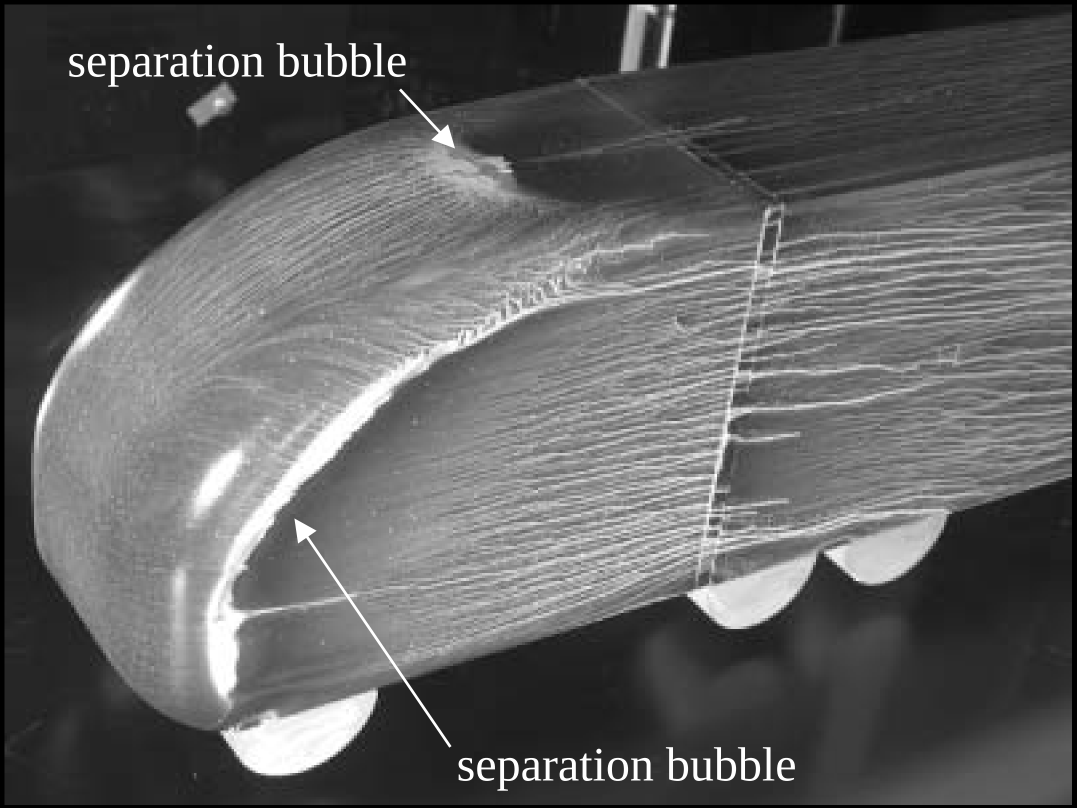


Flow Visualization Measurements



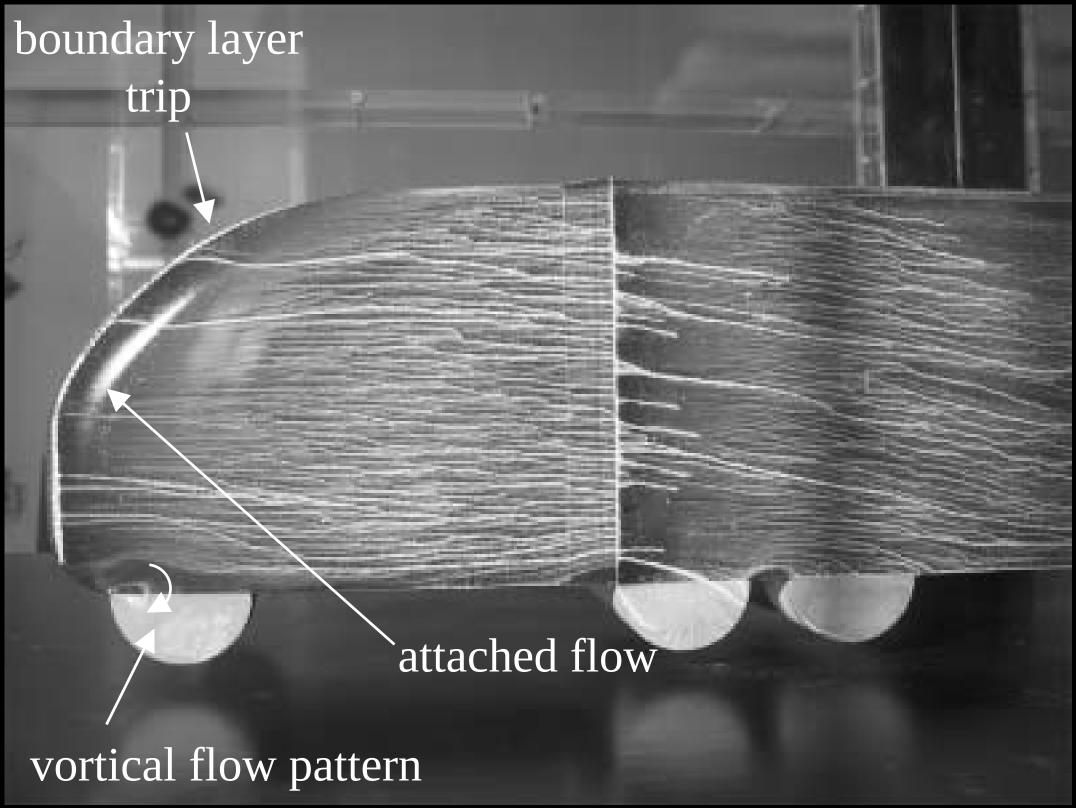
- MGTS model coated with ***white pigmented oil***
- Wind tunnel run for ~ 20 minutes to fully establish time-averaged flow field patterns
- Images of surface flow captured with $4.0\Delta10^6$ pixel digital camera

Flow Visualization Measurements



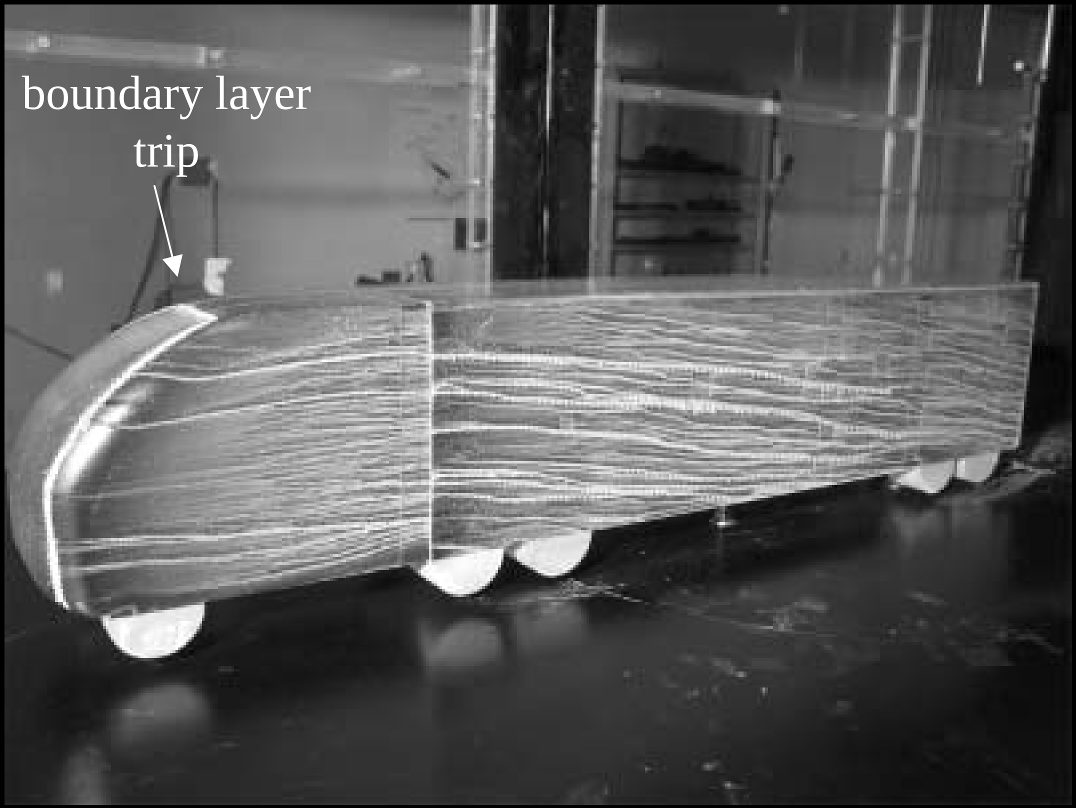
- Re_w = 461,000
- 0^o yaw angle
- MGTS model exhibits ***flow separation*** on ***sides*** and ***top*** of tractor
- Necessary to use ***boundary layer trips*** on tractor

Flow Visualization Measurements



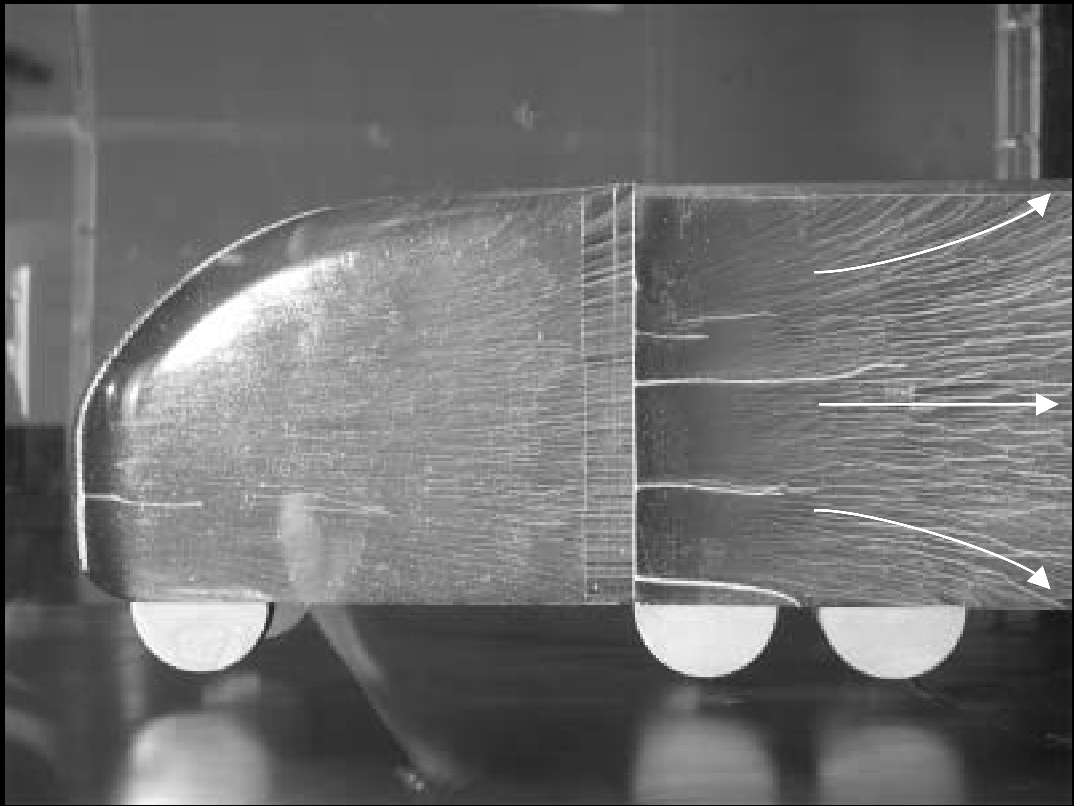
- $Re_w = 461{,}000$
- 0^o yaw angle
- ***Boundary layer trips*** keep the flow attached to the tractor

Flow Visualization Measurements



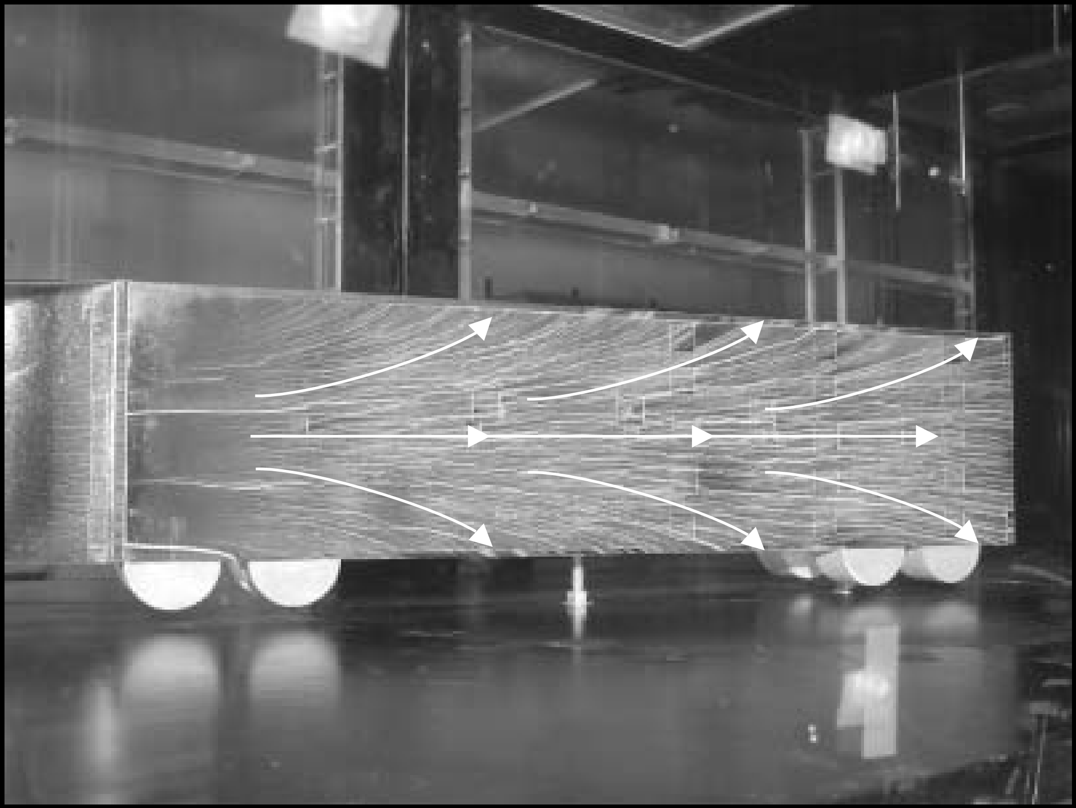
- Re_w = 461,000
- 0^o yaw angle
- ***Attached flow*** present down the length of the tractor and trailer

Flow Visualization Measurements



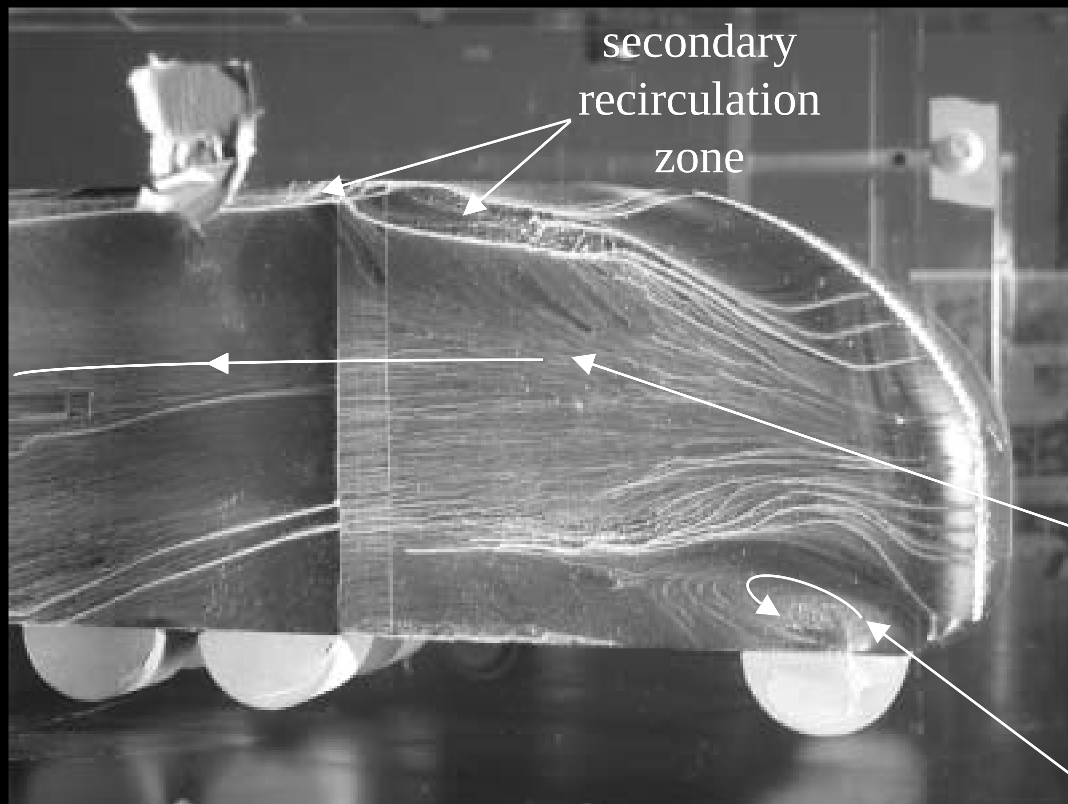
- Re_w = 461,000
- 14^o yaw angle
- ***Upstream*** side of the tractor/trailer

Flow Visualization Measurements



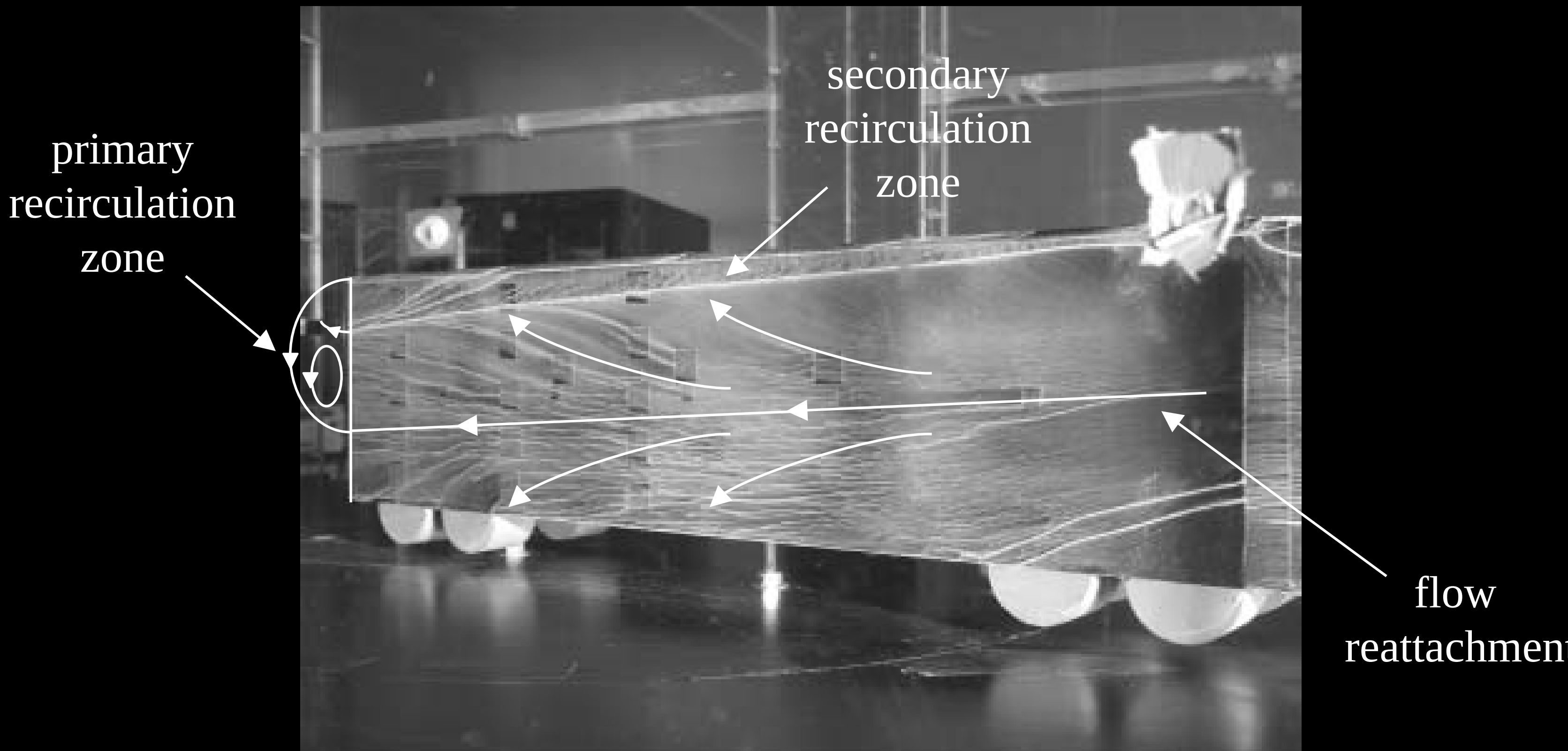
- Re_w = 461,000
- 14^o yaw angle
- ***Upstream*** side of the tractor/trailer

Flow Visualization Measurements



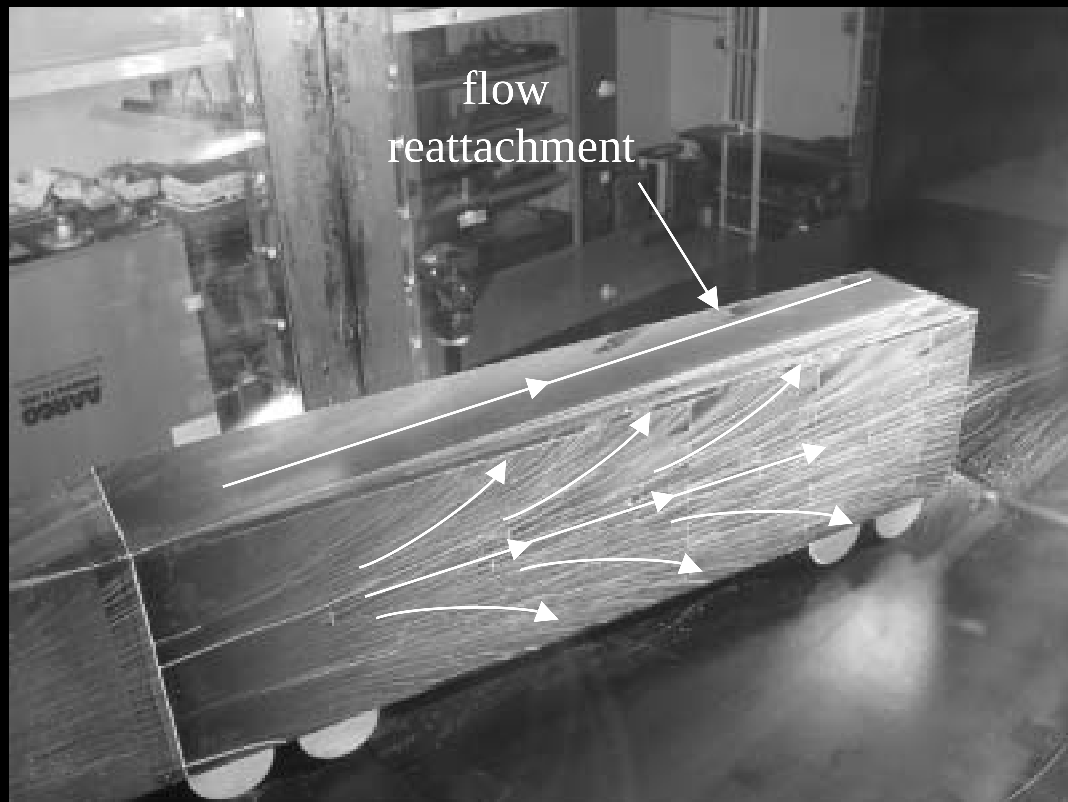
- $Re_w = 461{,}000$
- 14^o yaw angle
- ***Downstream*** side of the tractor/trailer

Flow Visualization Measurements



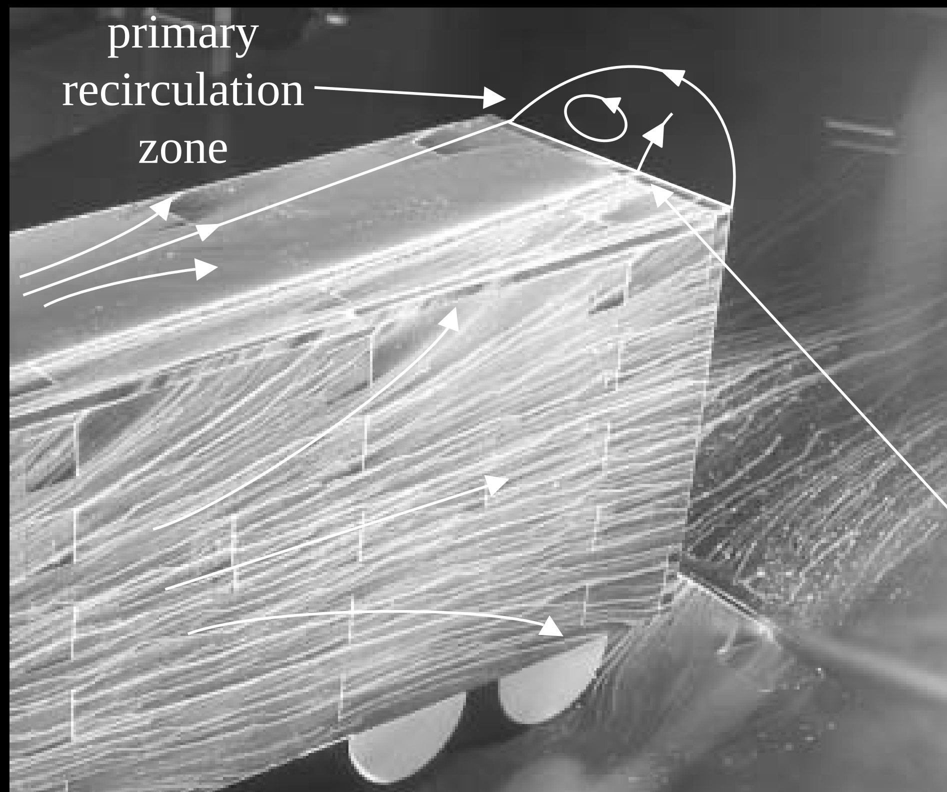
- $Re_w = 461{,}000$
- 14^o yaw angle
- ***Downstream*** side of the tractor/trailer

Flow Visualization Measurements



- $Re_w = 461{,}000$
- 14^o yaw angle
- ***Top*** of the tractor/trailer

Flow Visualization Measurements



- $Re_w = 461{,}000$
- 14^o yaw angle
- ***Top*** of the tractor/trailer

Conclusions

- ***Oil surface flow visualization*** measurements of MGTS geometry at $Re_w = 461{,}000$
- At 0º yaw:
  - ***boundary layer trips*** required to keep the ***flow attached*** to the tractor
- At 14º yaw:
  - ***complex, 3-D flow patterns*** form on the ***downstream*** side of the tractor
  - Trailer ***top*** and ***downstream side*** have recirculation zones that cover a ***significant portion*** of the trailer
  - How do these ***recirculation zones*** affect the performance of various ***add-on drag reduction devices***?

Future Work

- ***Force*** and ***moment*** measurements to test the effectiveness of drag reduction devices located on the trailer ***base*** and ***underside***
- Further optimization of the ***angled boattail plates*** concept

Acknowledgements

- Dennis Acosta, Kurt Long, Jim Ross, Dale Satran, Bruce Storms, and Dave Yaste of NASA Ames Fluid Mechanics Laboratory

‘Working Group Meeting’

Consortium for Aerodynamic Drag of Heavy Vehicles

Department of Energy, Office of FreedomCAR & Vehicle Technologies

May 30, 2003

James Ross, Dale Satran, J.T. Heineck, Steve Walker

National Aeronautics & Space Administration

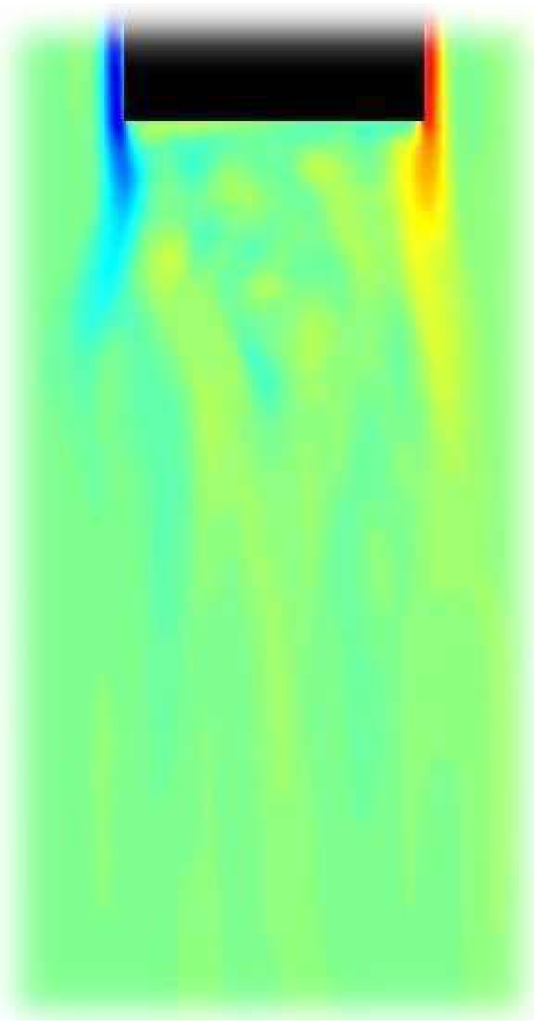
The FY03 deliverables provide near-term guidance to industry.

- **Completed testing in 12’ PWT - 4/03**
  - Reynolds number effects quantified for variety of flow regions and drag-reducing devices
- **PIV system upgrades complete**
- **Additional testing for aero loads and flow-field measurements**
  - Highest pressure 3.7 atm due to laser instabilities
  - Gap flow well documented up to full-scale highway Re ($5x10^6$)
  - Wake flow partially documented - laser failure precluded completion of entire test matrix
- **Base flap optimization runs completed**
  - Highest drag reduction at full Re achieved with 16° deflection
- **Publications**
  - 2 papers presented at December UEF conference - written versions in by
  - NASA TM documenting 7x10 tests of GCM in works - complete by 10/03
  - NASA TM documenting 12’ PWT tests - now scheduled to be done by 1/04
- **Discovery tests of LLNL devices in FML Test Cell 3 underway**
  - Some pressure data obtained
  - Drag data soon. Delay due to fallout of closure of 12’ PWT and 40x80x120 at Ames.

FY04 plans push into new areas with big impact.

- **Collaboration with LLNL in Discovery experiments at FML TC-2**
- **Underbody flow experiments in water channel and TC-2 (and USC wind tunnel?)**
- **Data analysis and publication**
  - Complete documentation of 12’ PWT test results (1/04)
- **Support of Tiger Team activities**

- Prof. Anthony Leonard
- Philippe Chatelain
- Mike Rubel



Vortex Methods: Essentials

- Numerical technique to solve the Navier-Stokes equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of velocity) as the solution variable
- Computational elements move with fluid velocity
- Viscous, 3-D, incompressible, with boundaries

Vortex Methods: Advantages

Mike Rubel
Caltech

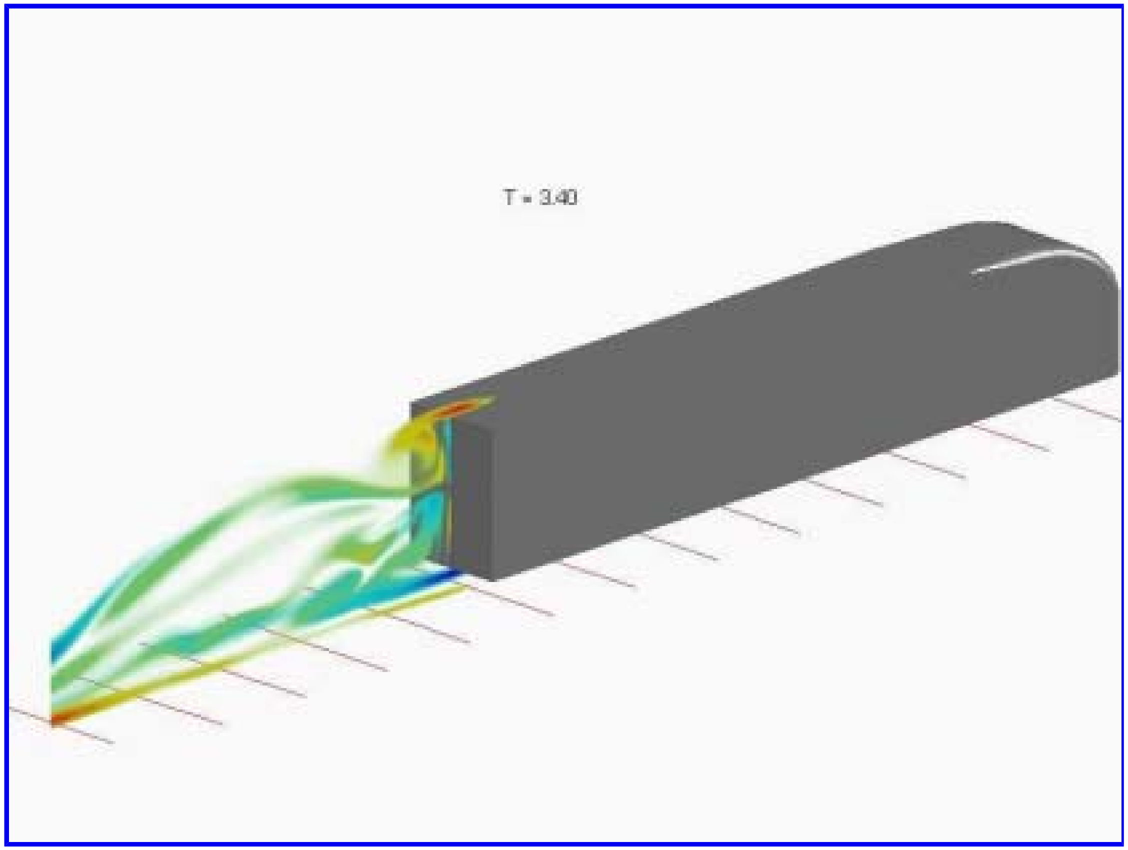
- Computational elements only where vorticity is finite
- No mesh in the flow field
- Only 2-D grid on the vehicle surface
- Boundary conditions in the far field automatically satisfied

Topics Outline

- GTS geometry high resolution wake flow with ground effect
- Time average of lower-resolution GTS wake flow
- Viscous boundary conditions for solid body rotation
- C/OT Closest point transform algorithm: scalings and paper
- Multiscale Time Integration

High-Resolution GTS Wake Run

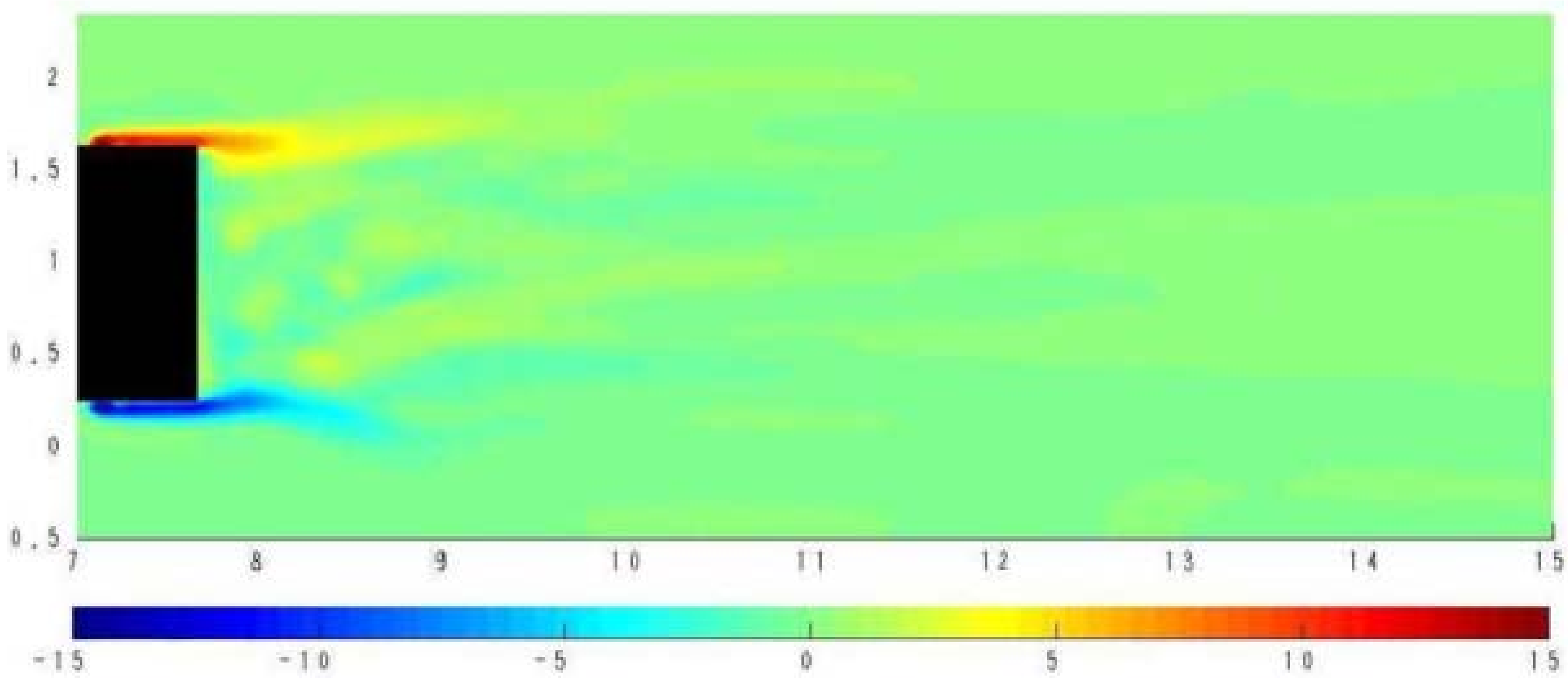
Mike Rubel
Caltech



Time-Average of Wake Flow

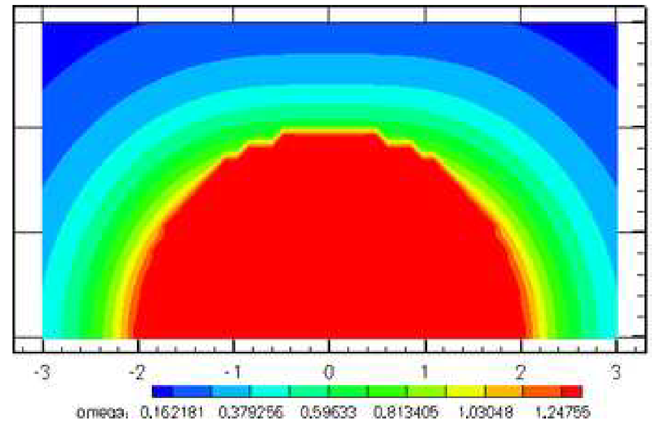
Mike Rubel
Caltech

- Lower-resolution run, no ground plane, Re 10^3-ish, avg over one length
- Vertical slice of Y-vorticity through midplane

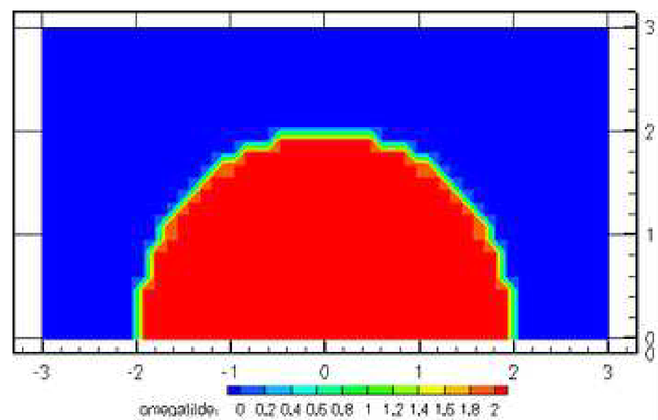


Mike Rubel
Caltech

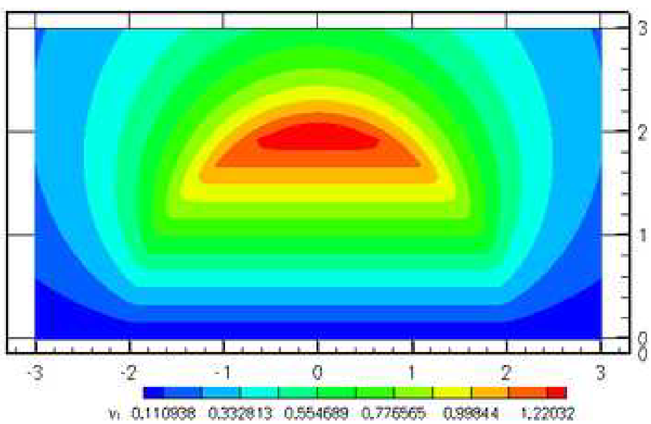
- Need to take into account vorticity inside spinning body
- Can avoid volume integral, transform to surface integral
- New kernel implemented in the fast panel code



Curl of velocity

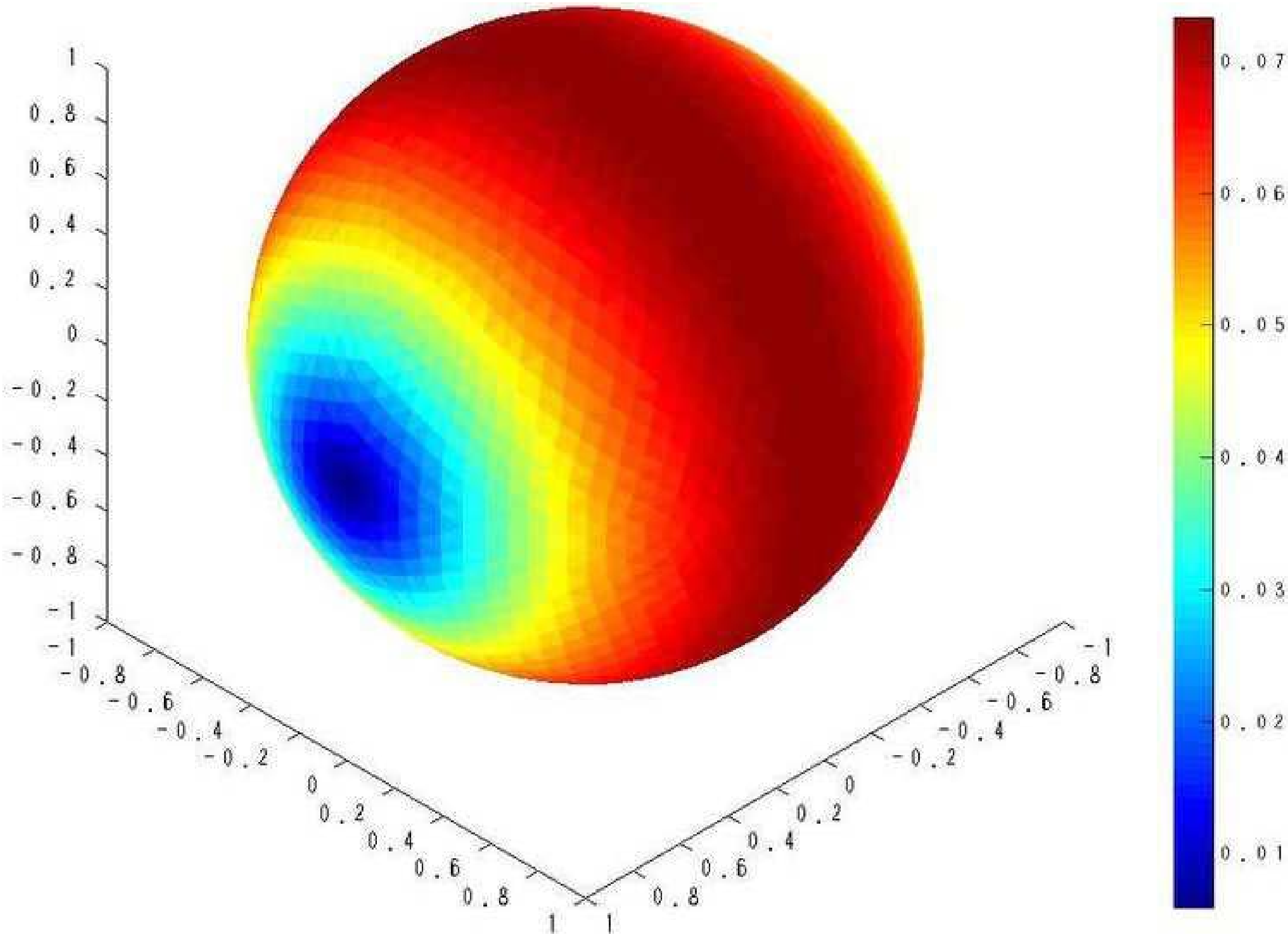


Vorticity



Velocity Magnitude

Mike Rubel
Caltech

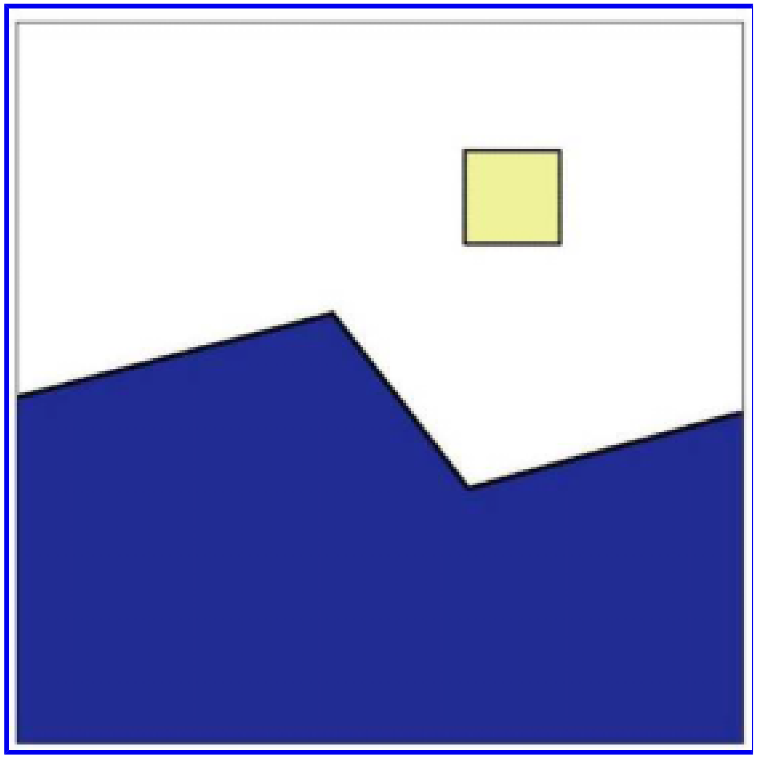


Vorticity flux magnitude on sphere surface

C/OT Closest Point Transform Algorithm

Mike Rubel
Caltech

- Two implicit algorithms investigated: Least Upper Bound (LUB) and Characteristic / Octree (C/OT), constant work per test point
- Memory scaling 3/2 power for C/OT



New Article on CPT

Mike Rubel
Caltech

- Wrote new article comparing implicit closest point transform algorithms, preparing to submit.
- Provides theoretical and experimental scalings
- CPT algorithm integrated into vortex code

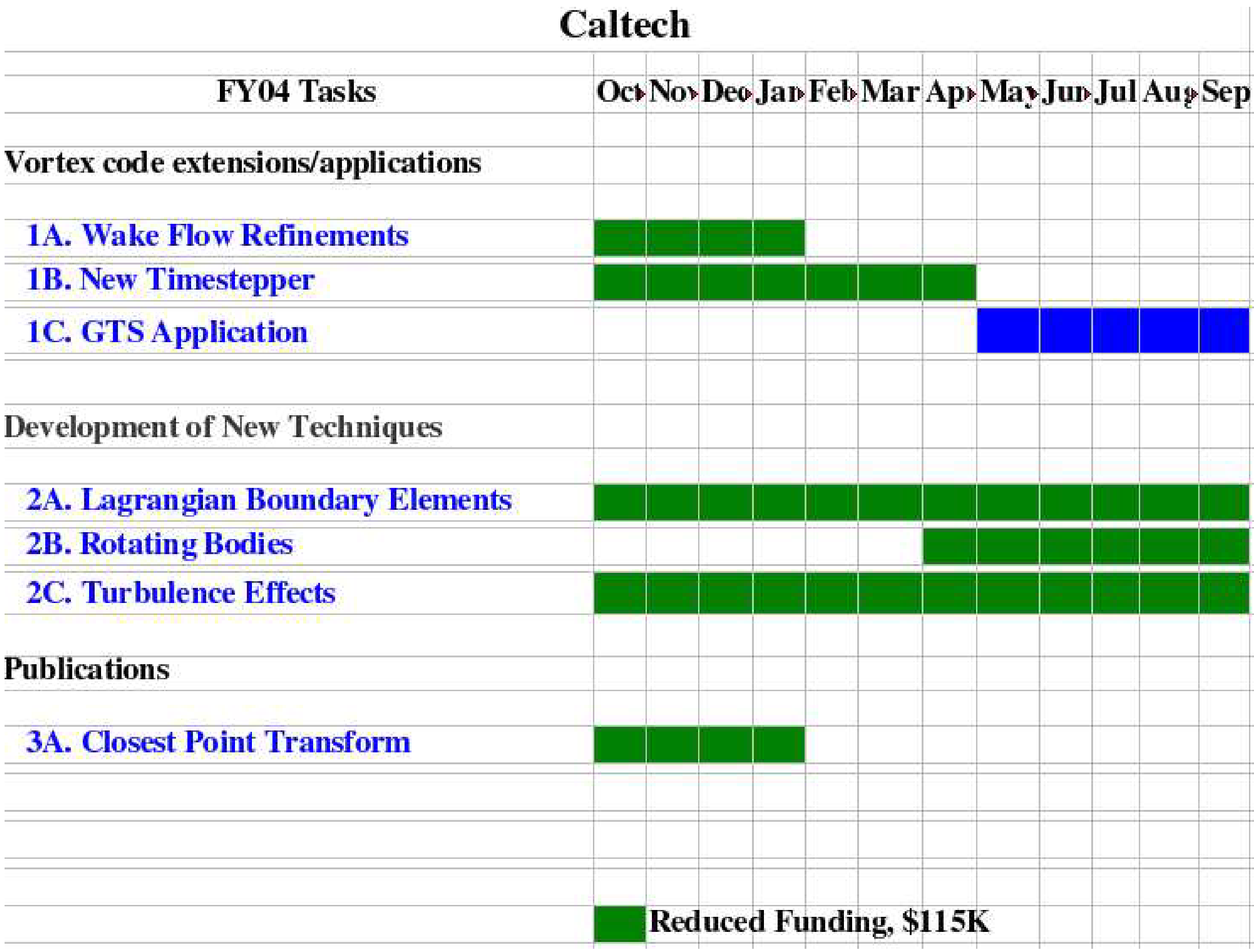
Multiple Scale Time Integration

Mike Rubel
Caltech

- Notice particles tend to operate at different time scales, no way to take advantage of scale difference using standard adaptive stepping techniques
- Look to *asynchronous* approaches, such as Dead Reckoning
- Dead reckoning wake-ups not scaling well to dense operator; modifying to support standard adaptive step-size condition
- This term: programming, theoretical work on stability

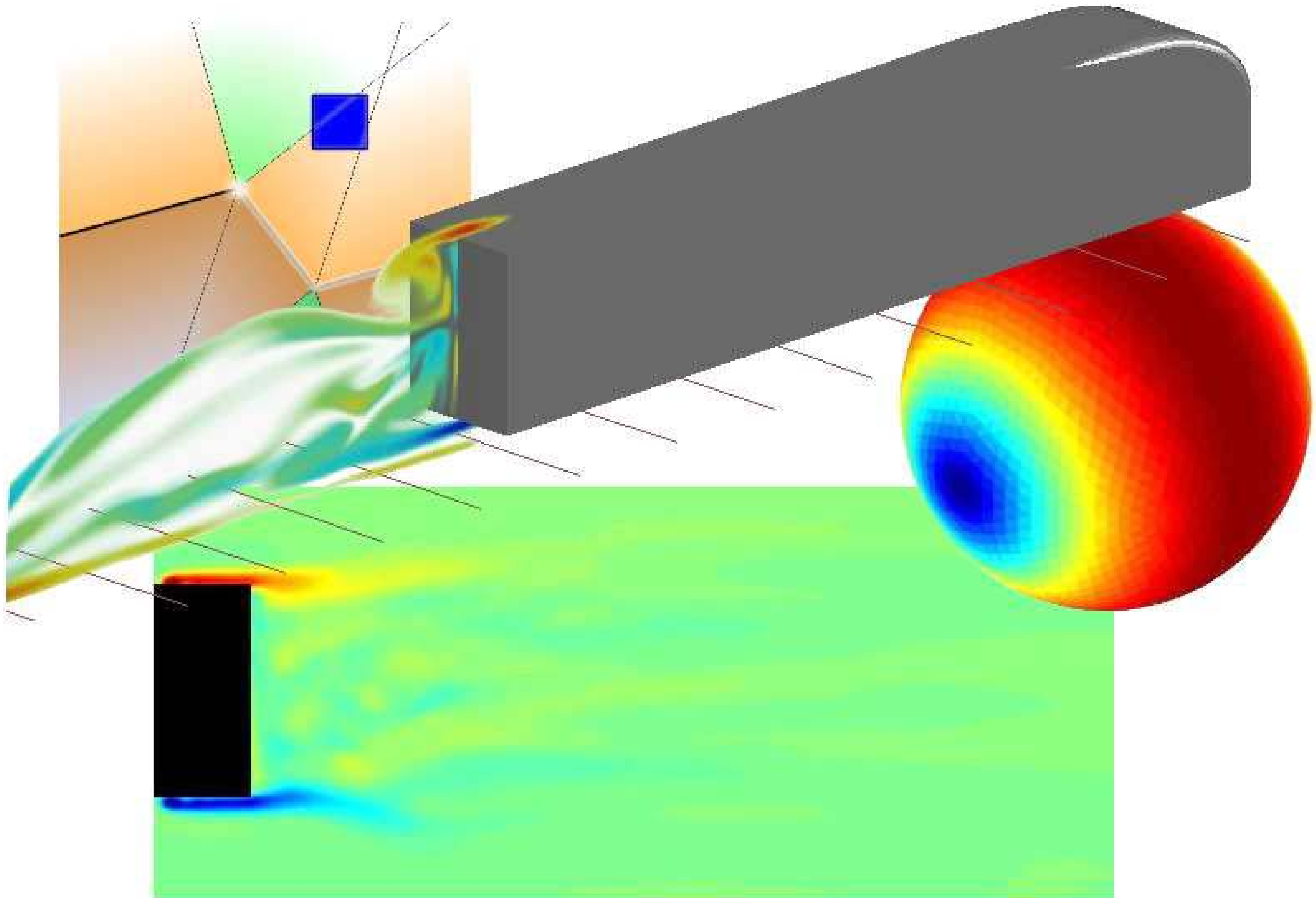
2004 Planned Work: Chart

Mike Rubel
Caltech



2004 Planned Work Summary

- Cutoff for closest point transform to further reduce memory consumption
- Viscous attached panels: receive viscous flux from wall, do particle interaction
- Force measurements on viscous attached panels.
- Send CPT article in for publication
- Multiscale integrator adjustments and theory



RANS and Hybrid RANS/LES of Bluff Body Flows

Chris Roy, Larry DeChant, Jeff Payne, and Mary McWherter-Payne

Engineering Sciences Center
Sandia National Laboratories
Albuquerque, New Mexico

Introduction

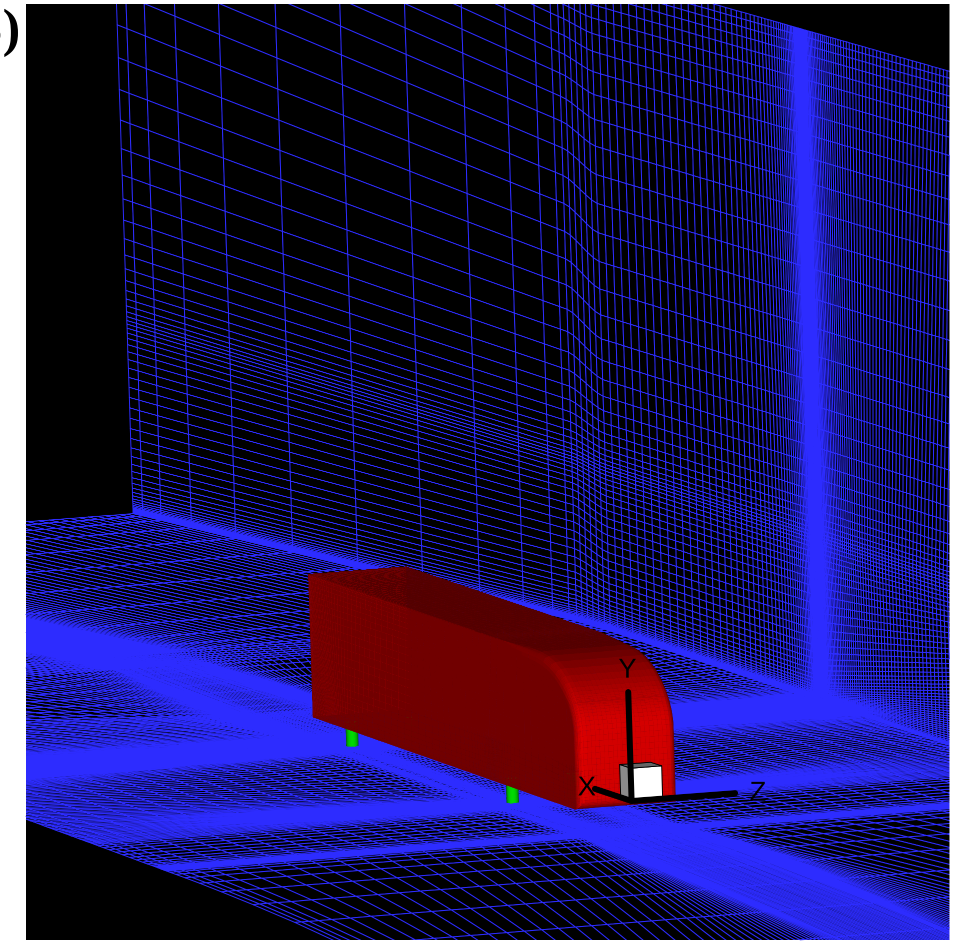
- **Modeling and simulation code: SACCARA**
- **Compressible Navier-Stokes equations**
- **Symmetric TVD upwind scheme**
- **Massively parallel, multiblock structured grids**
- **Two turbulence models**
    - **Menter hybrid k-κ/k-ϖ model**
    - **Spalart-Allmaras 1-equation model**

    ü **both are integrated to the wall**
- **Goal: validate CFD with RANS models for tractor/trailer aerodynamics**

Problem Formulation

- Ground Transportation System (GTS)
- Class 8 tractor/trailer (1/8 scale)
  - L = 2.48 *m* (97.5 *in*)
  - W = 0.324 *m* (12.75 *in*)
- Re_W = 2 million
- M_{inf} = 0.27
- u_{inf} = 91.6 *m/s* (205 *mph*)
- p_O = 102.65 *kPa*
- T_O = 282.1 *K*

GTS in Ames 7’Δ10’ tunnel
(NASA/TM-2001-209621)



GTS Computational Mesh
(2.5 M Grid Points)

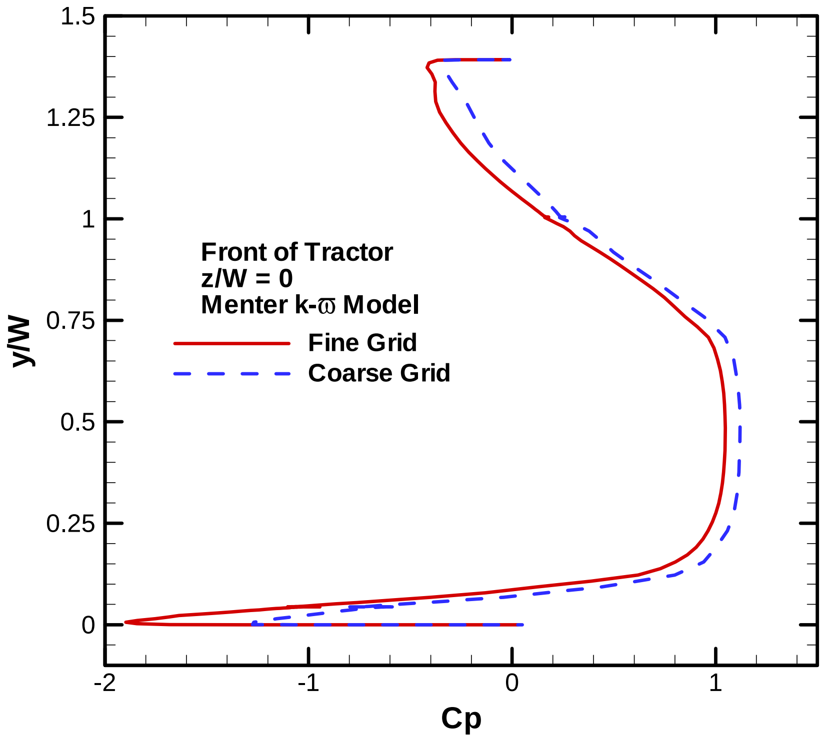
Numerical Accuracy

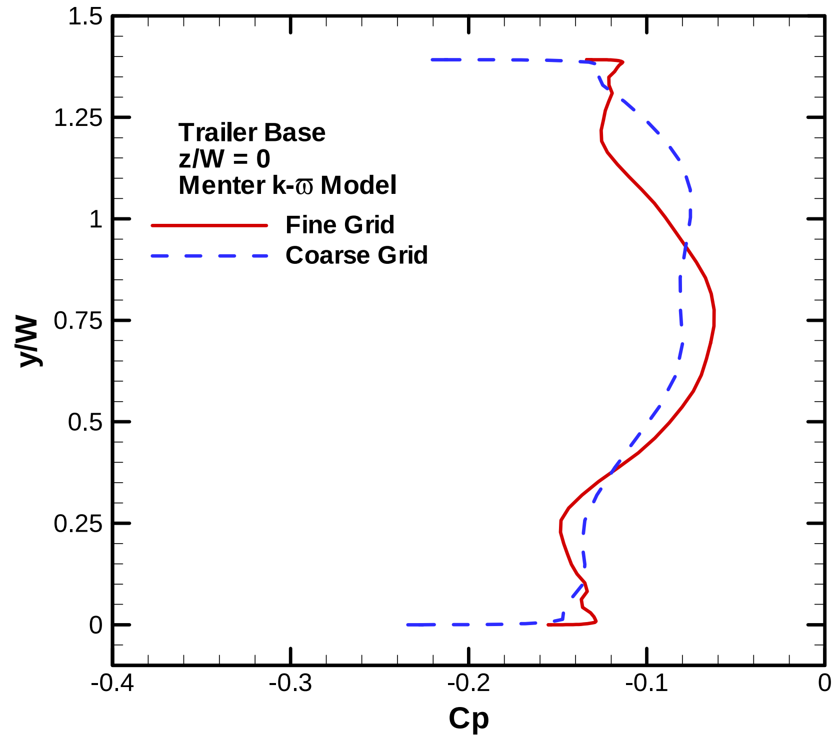
- **Iterative convergence**
  - **L2 norms of steady-state momentum equations reduced by at least 6 orders of magnitude**
- **Spatial convergence**
  - **two mesh levels**
    - **coarse: 2.5 million cells**
    - **fine: 20 million cells**
  - **use Richardson extrapolation to approximate exact solution, evaluate error in discrete solutions**
  - **Menter k-ϖ solutions used for grid study**

Numerical Accuracy

Front

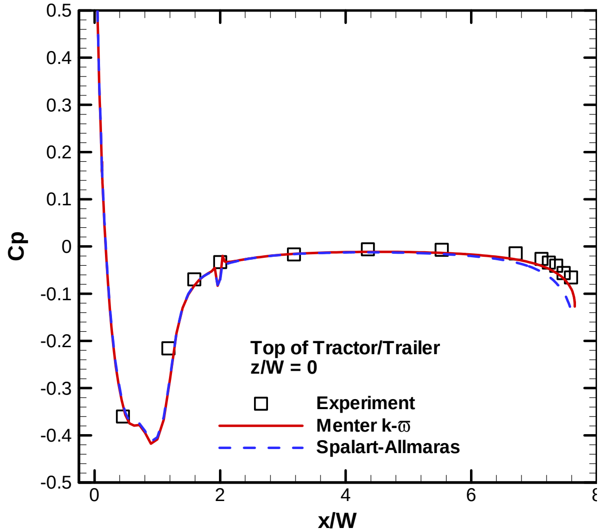
Back



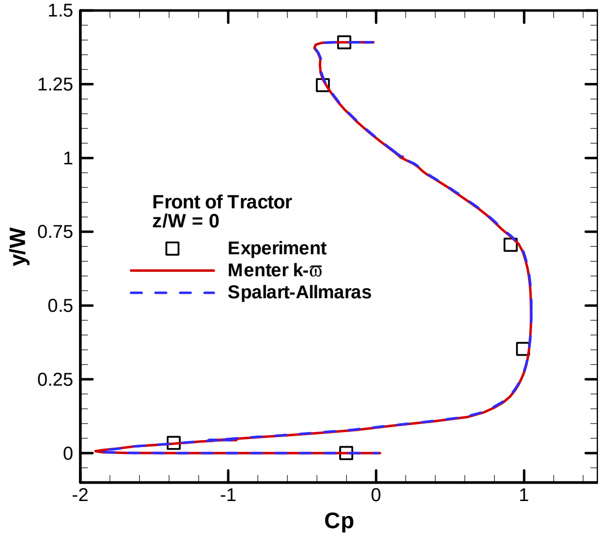


Surface Pressure

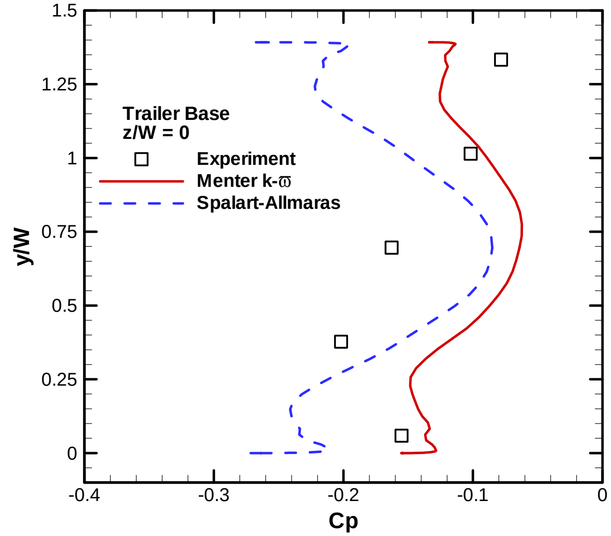
Surface Pressures: *z/W = 0*



Top of Tractor/Trailer



Front of Tractor



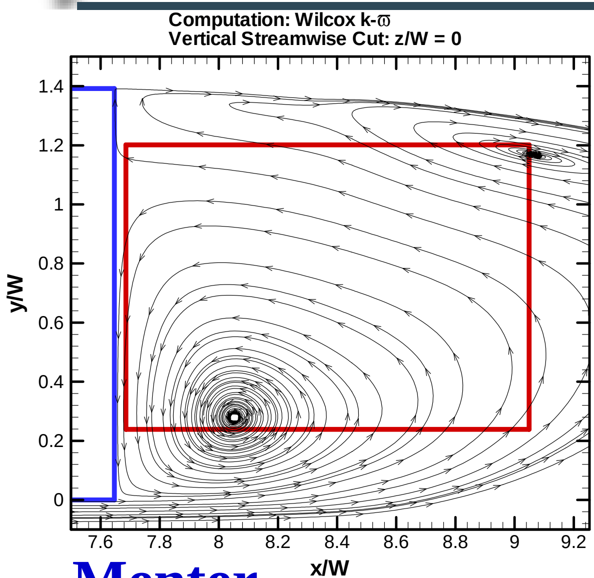
Base of Trailer

	C_D
Expt.	0.25
Menter	0.298
Spalart	0.413

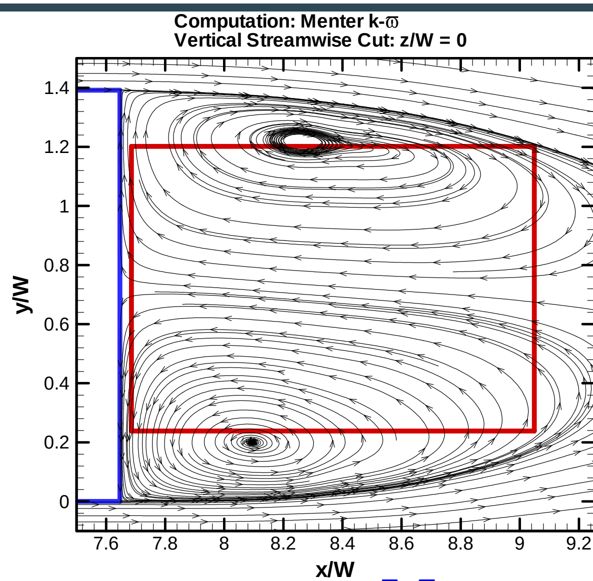
Drag Coefficient

- RANS accurate on front & top
- Problems are in base region
- Spalart-Allmaras overpredicts C_D
- Menter accurately predicts C_D, but misses *details* in wake

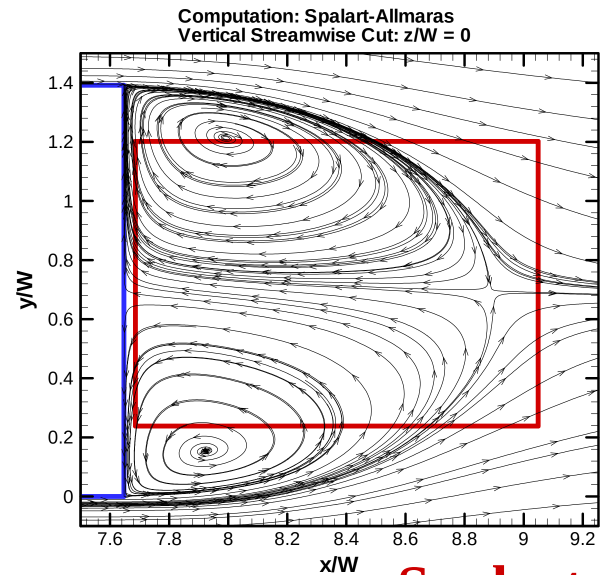
Trailer Wake: *z/W = 0*



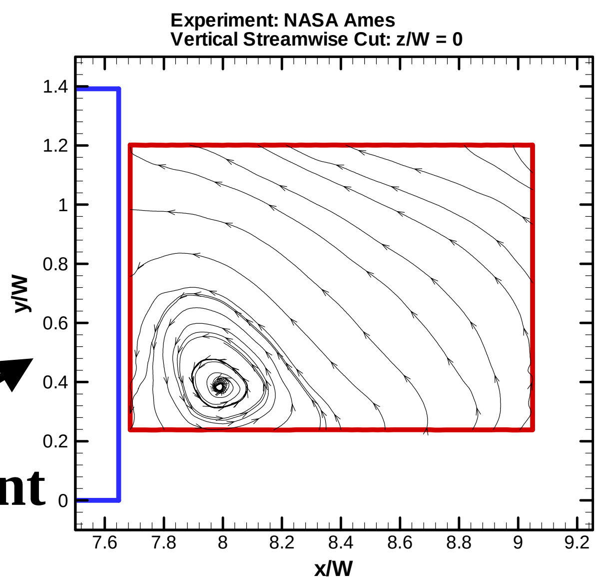
Menter (coarse)



Menter (fine)



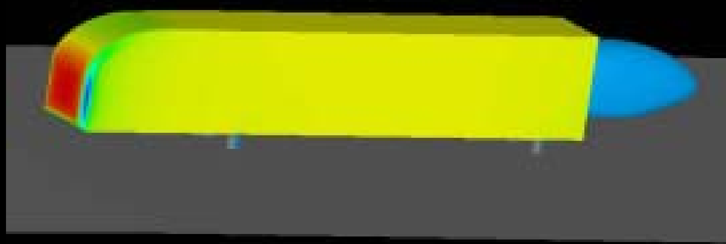
Spalart (fine)



Experiment

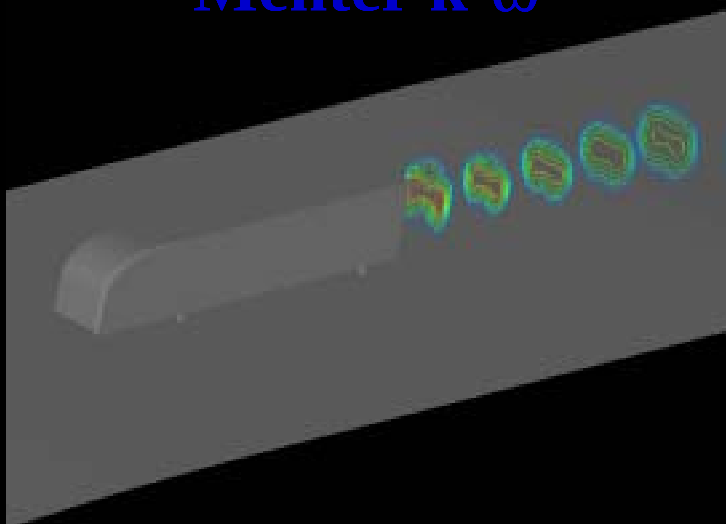
- **Menter k-omega model**
  - **coarse mesh (2.5 mill. cells) appears to capture wake**
  - **fine mesh (20 mill. cells) shows that wake prediction is poor**
- **Spalart: shorter, symmetric wake**

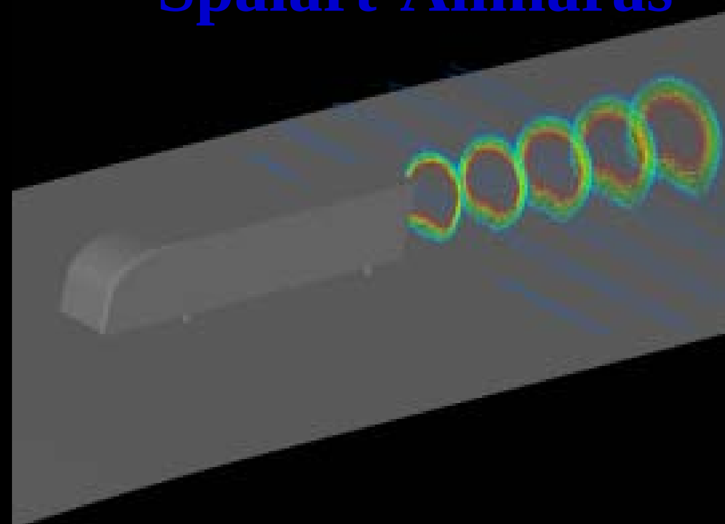
Flowfield Features



Recirculation Zone

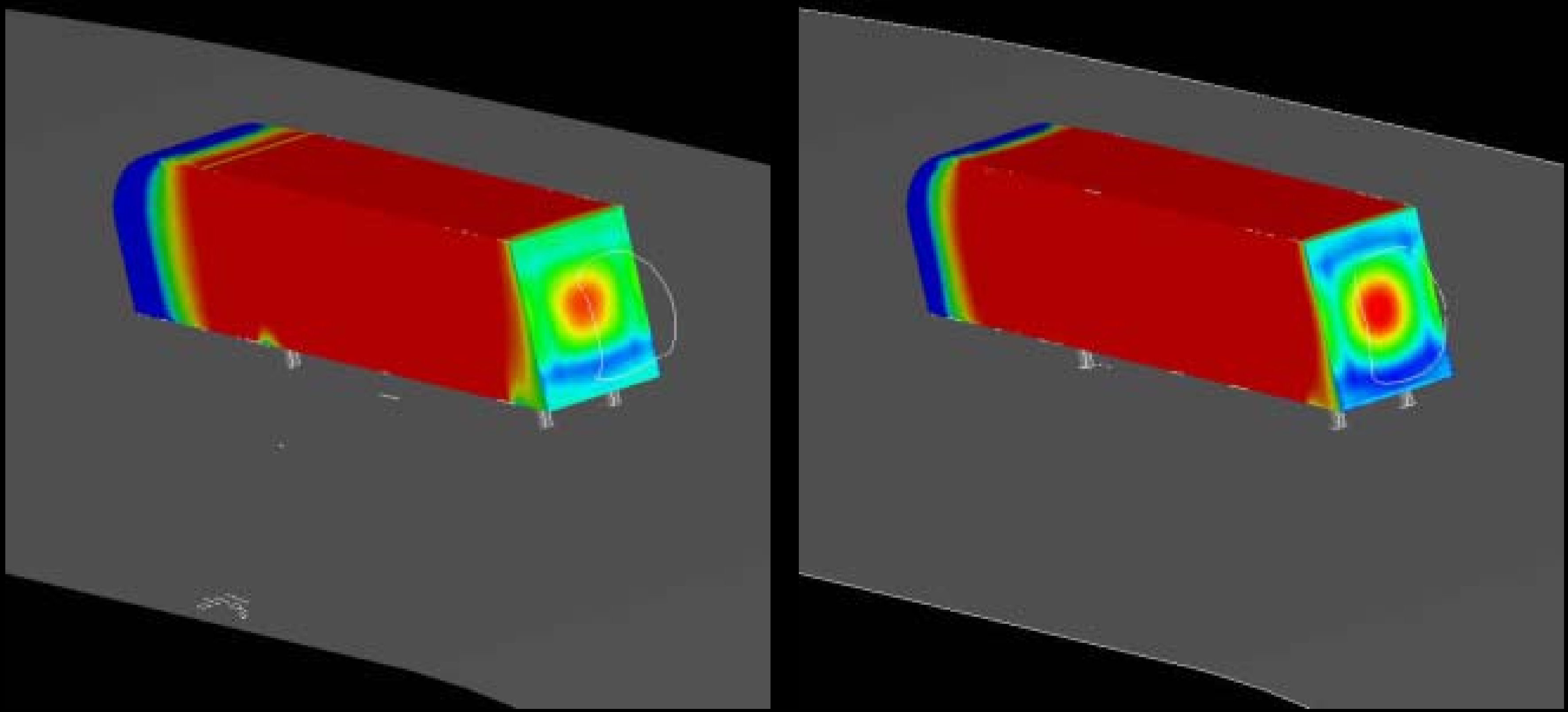
Menter k-ϖ **Spalart-Allmaras**





Total Viscosity

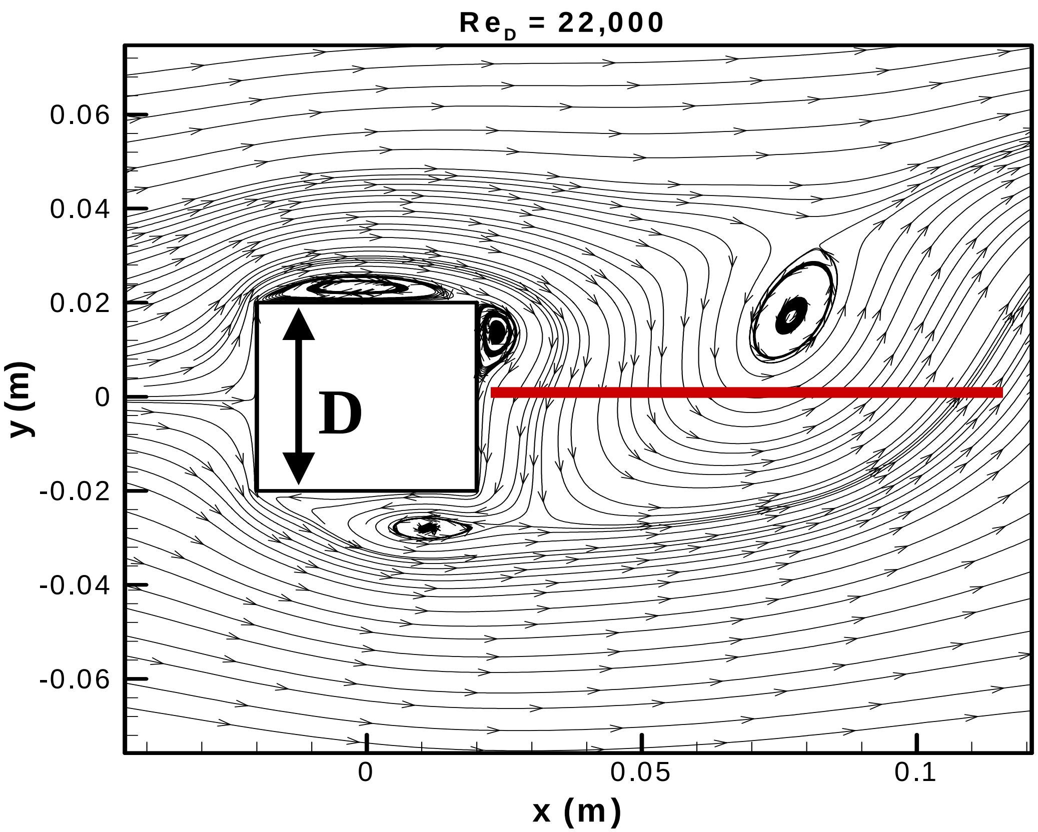
Flowfield Features



Menter k-ϖ **Spalart-Allmaras**

Vortex Cores and Base Pressure Contours

ESRF Leveraging
Square Cross-Section Cylinder



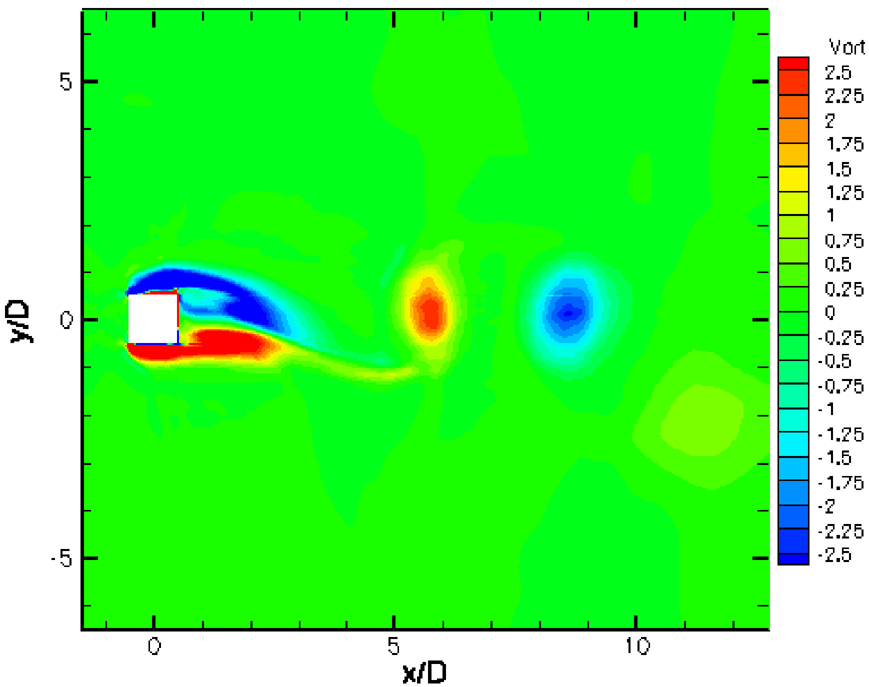
Square Cross-Section Cylinder
D∆D, Re = 21,400

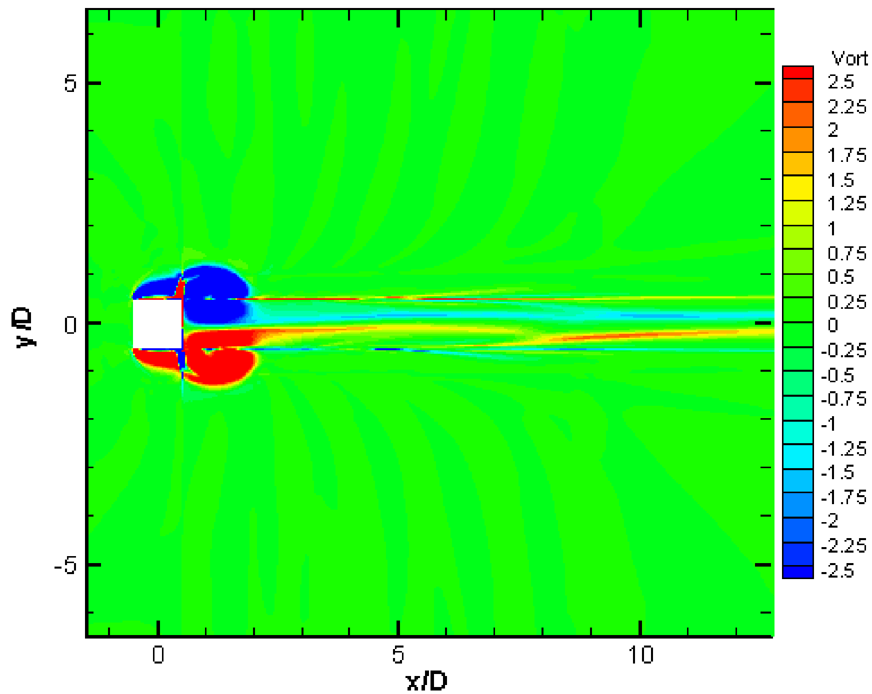
- **2D steady-state RANS**
  - **Spalart-Allmaras**
  - **Low Re k-epsilon**
  - **Menter k-omega**
  - **Wilcox k-omega**

  ü **all integrated to wall**

  ü **fine mesh results shown**
- **Spalart's Detached Eddy Simulation (DES)**
  - **2D (coarse, medium, fine)**
  - **3D (medium mesh only)**
- **Experimental PIV data**
  - **Lyn et al., 1995**
  - **Durao et al., 1988**

Square Cross-Section Cylinder

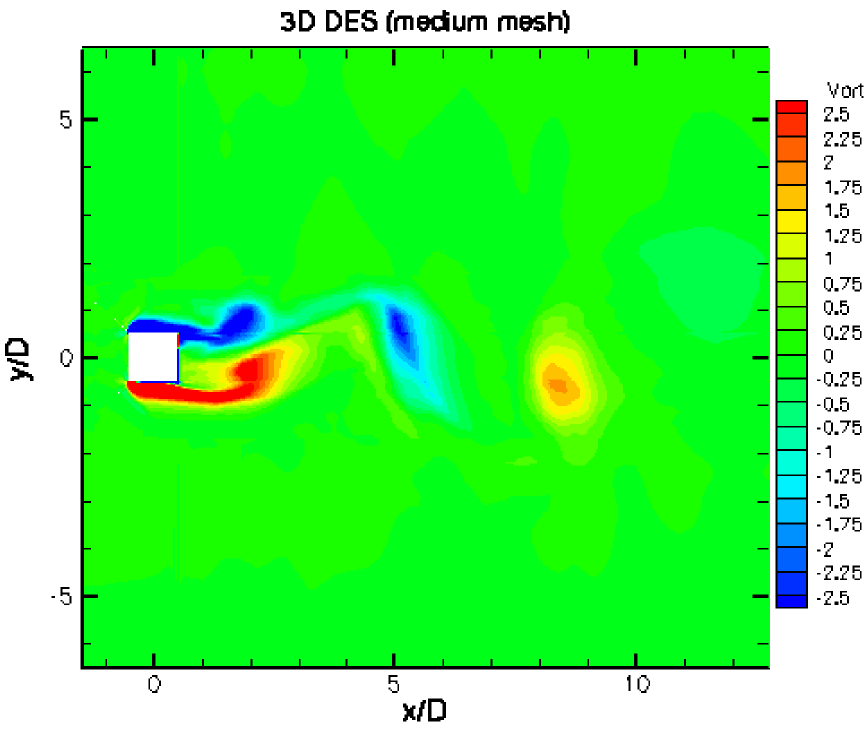


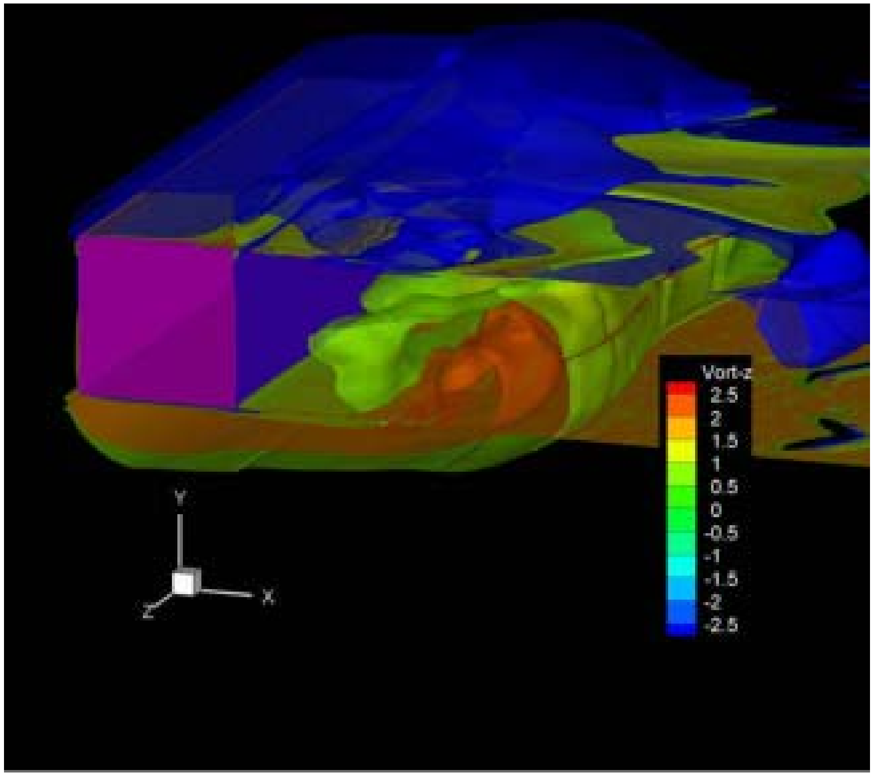


Medium Mesh (40k cells) **Fine Mesh (160k cells)**

2D DES: Vorticity Contours

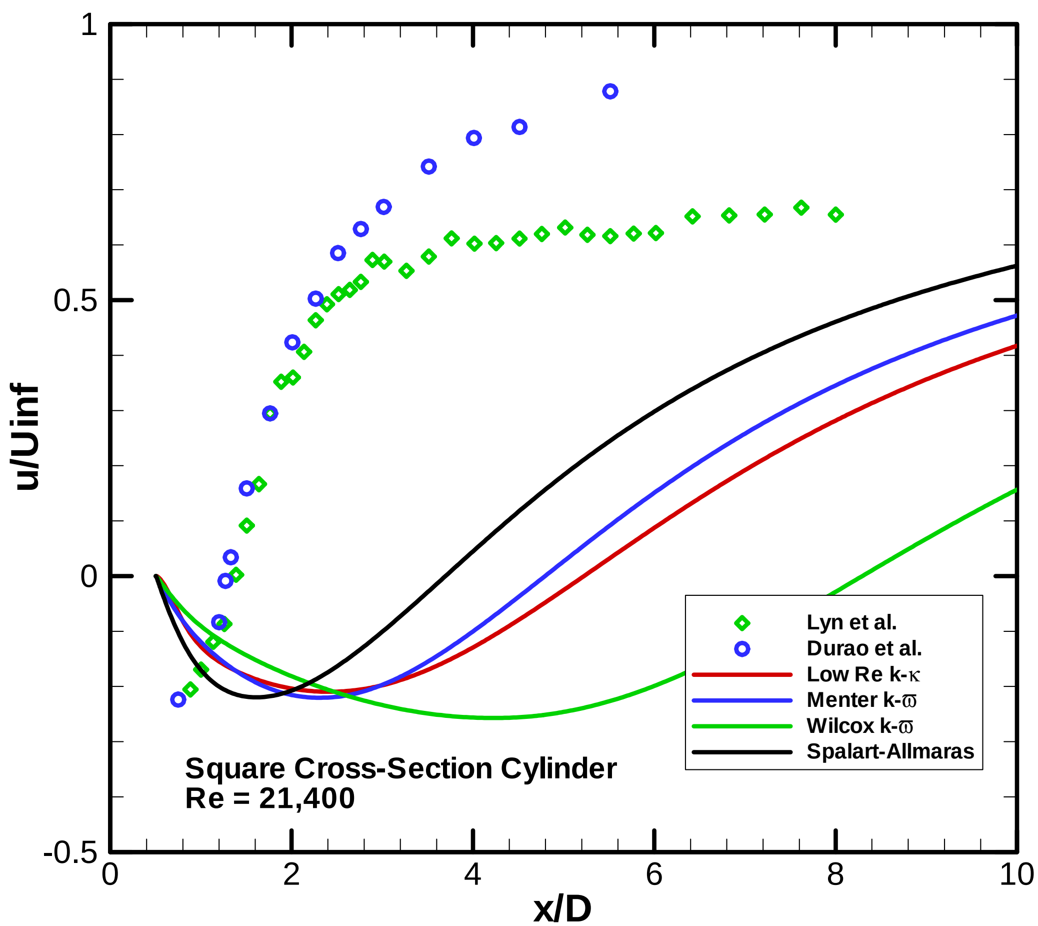
Square Cross-Section Cylinder





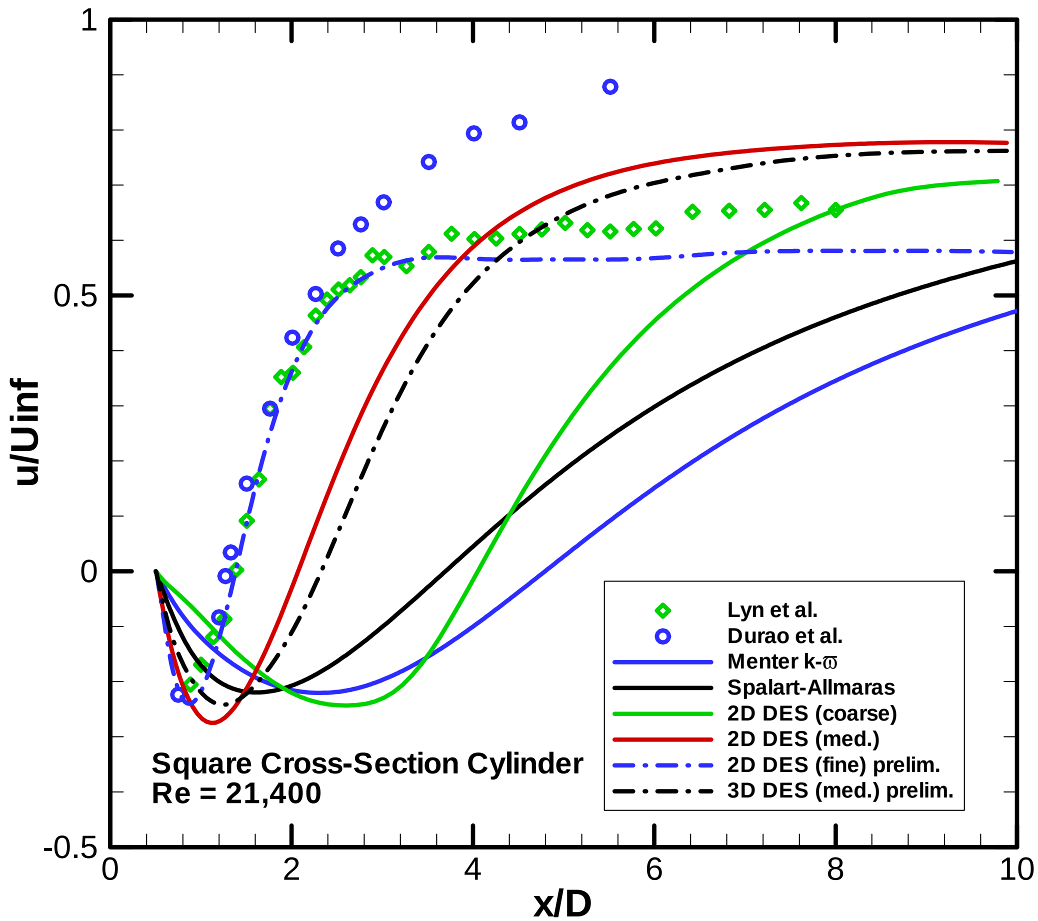
3D DES: Vorticity Contours
Medium Mesh (3.1M cells)

Square Cross-Section Cylinder



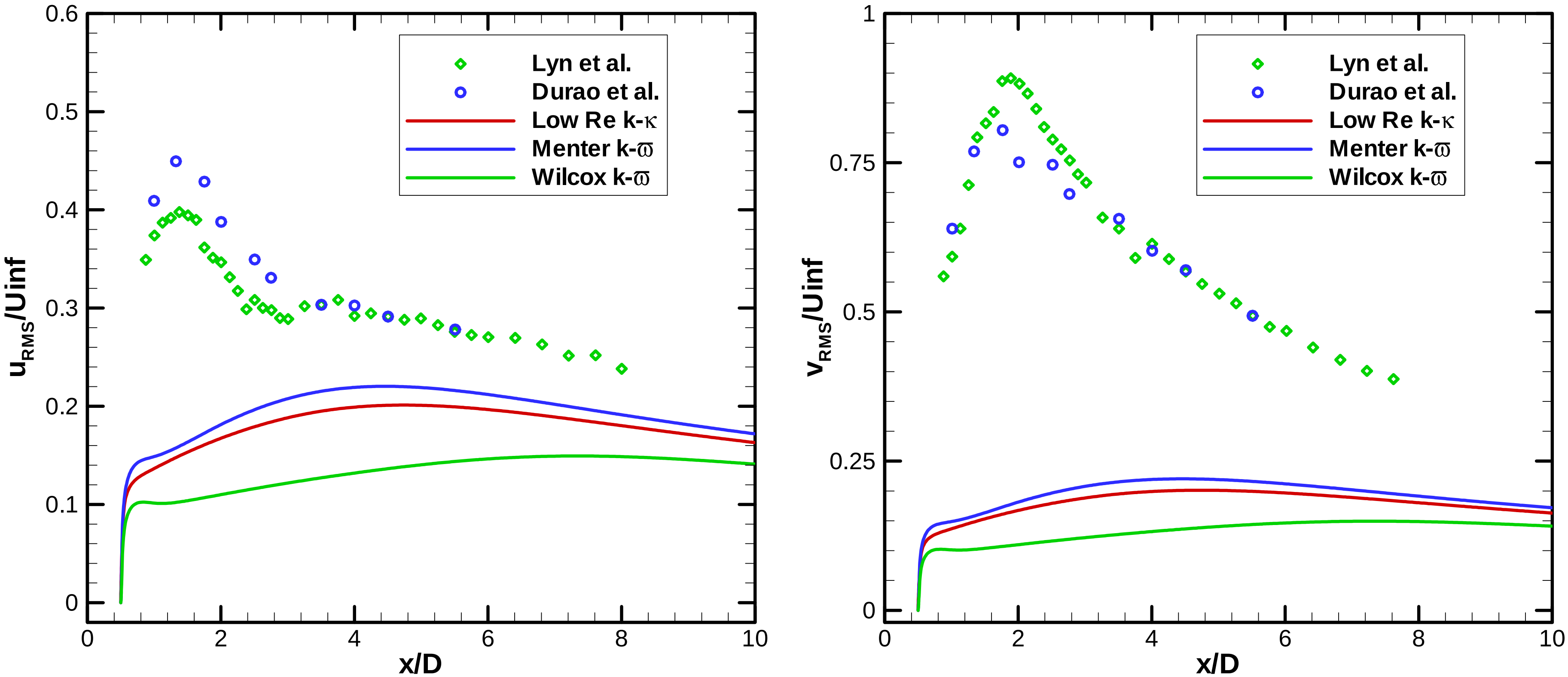
Centerline Wake Profiles: RANS

Square Cross-Section Cylinder



Centerline Wake Profiles: DES

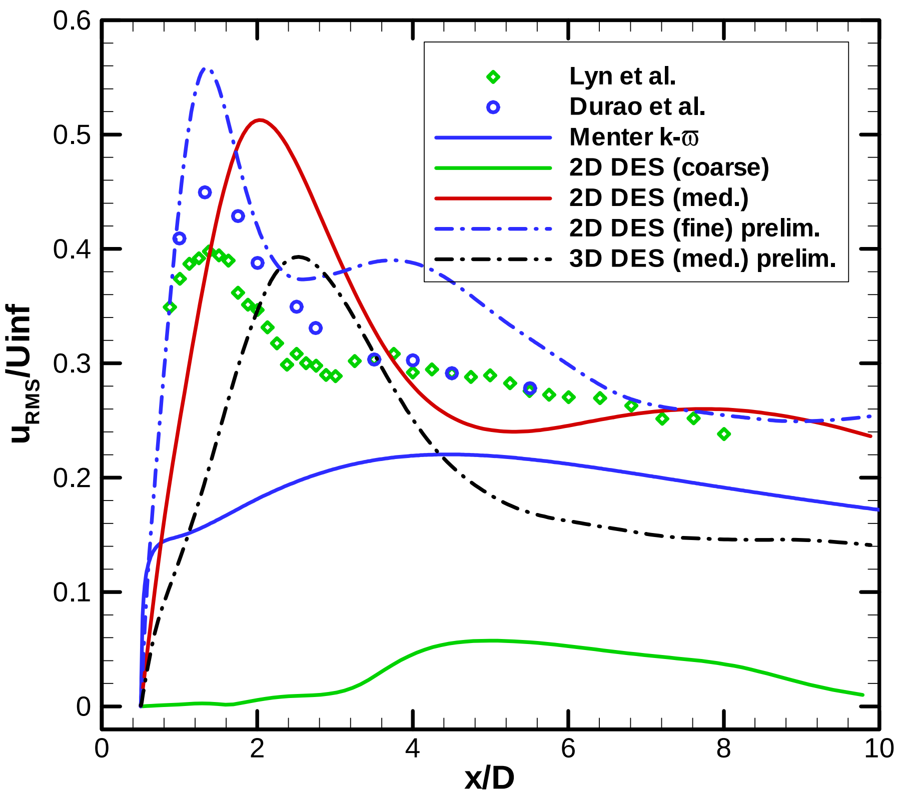
Square Cross-Section Cylinder

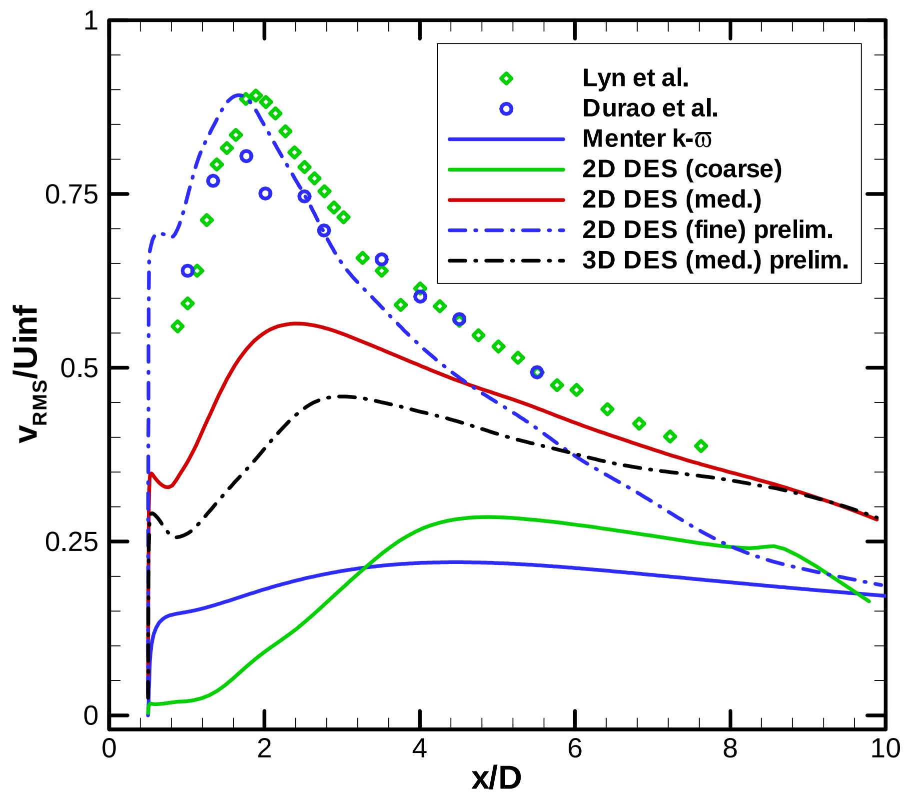


u_{RMS} v_{RMS}

Centerline Wake Profiles

Square Cross-Section Cylinder

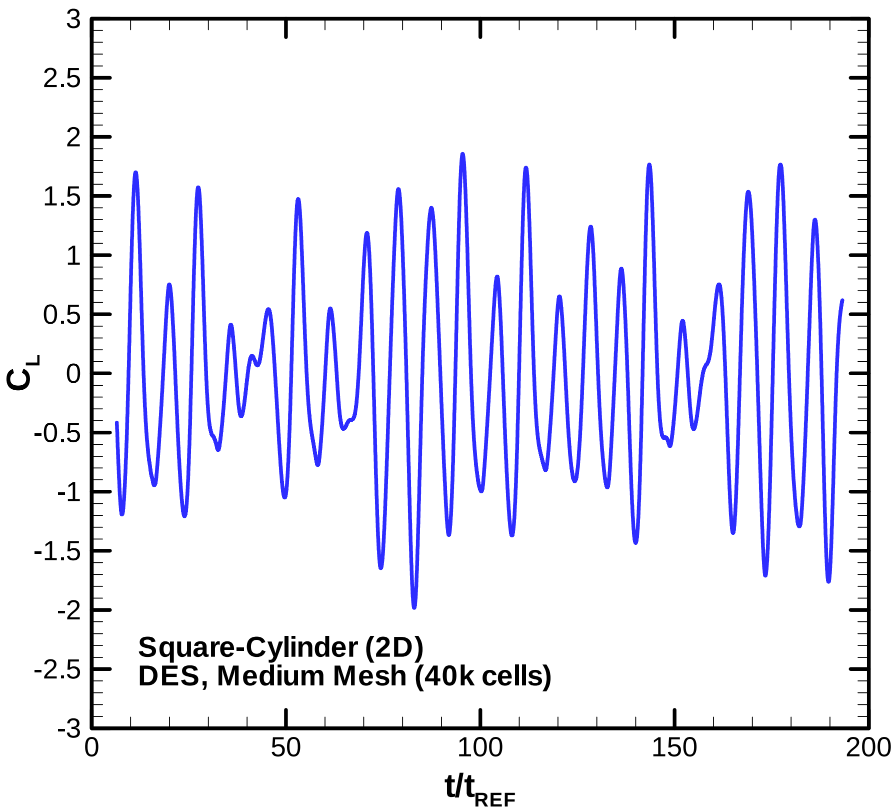


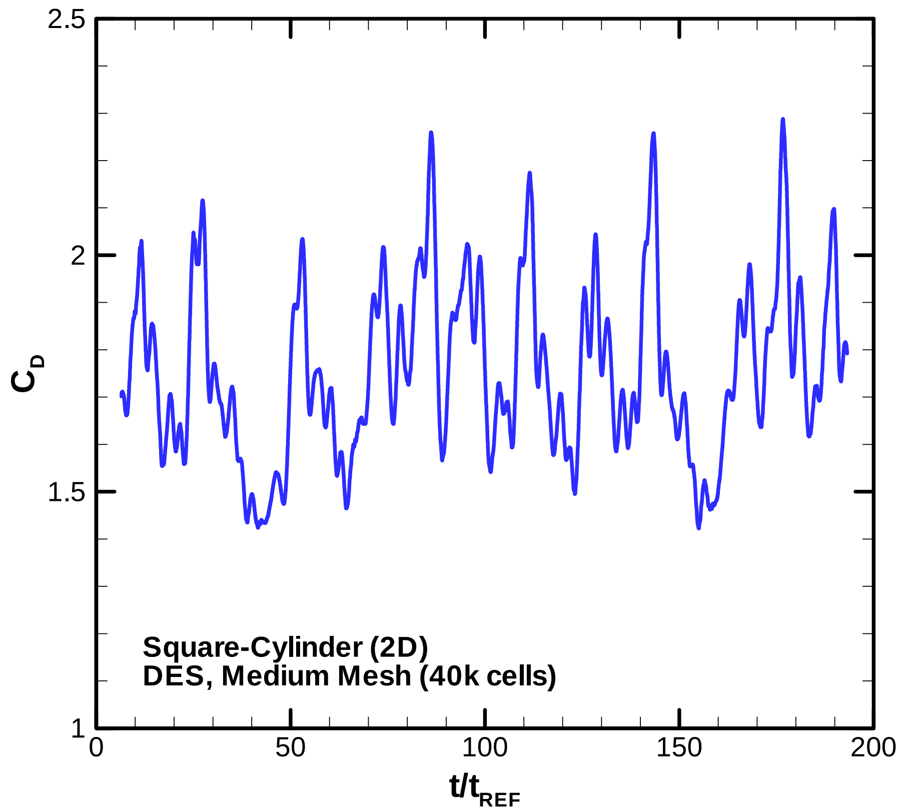


u_{RMS} v_{RMS}

Centerline Wake Profiles

Square Cross-Section Cylinder





Lift Coefficient **Drag Coefficient**

2D DES (Medium Mesh)

Square Cross-Section Cylinder

Global Quantities:

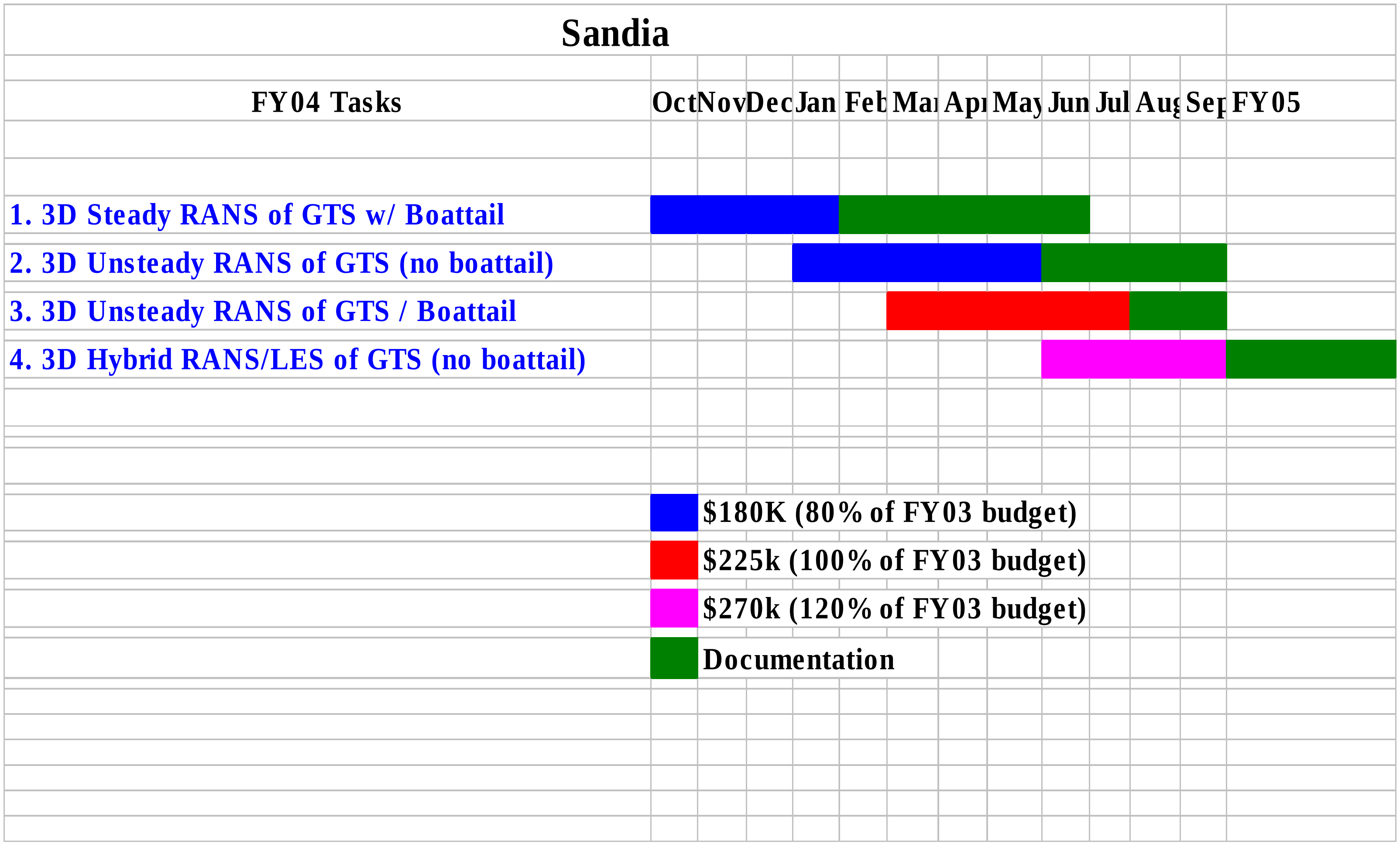
- Drag Coefficients
  - RANS: all underpredict C_D
  - DES: approaching expt.
- Reattachment Length (l_R/D)
  - RANS: all overpredict l_R/D
  - DES: approaching expt.
- Strouhal # (shedding freq.)
  - coarse DES: 0.138
  - medium DES: 0.123
  - experiment: 0.132

	C_D	l_R/D
Experiment	2.1	1.38
Low Re k-κ	1.52	5.22
Menter k-ϖ	1.58	4.79
Wilcox k-ϖ	1.53	8.29
Spalart-Allmaras	1.64	3.70
DES (coarse)	1.62	4.05
DES (medium)	1.80	2.07

Conclusions

- RANS models at high Re (GTS):
  - can predict global quantities
  - cannot predict local flow features
  - Menter k-ϖ more accurate than Spalart-Allmaras
- RANS models at lower Re (square cylinder):
  - cannot predict quantities (local or global) when dominant large-scale flow structures exist
  - improved accuracy of Spalart-Allmaras model may be due to luck -- shorter recirculation zone
- Hybrid RANS/LES (DES) model:
  - can more accurately reproduce flowfield details
  - medium mesh DES much better than fine mesh RANS
  - may provide improved accuracy for higher Re flows

Sandia FY04 Tasks and Budget



Overview of LLNL Effort

Jason Ortega, Kambiz Salari, Rose McCallen

Lawrence Livermore National Laboratory

Heavy Vehicle Aerodynamic Drag Working Group Meeting
May 29-31, 2003

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

LLNL FY03 Tasks

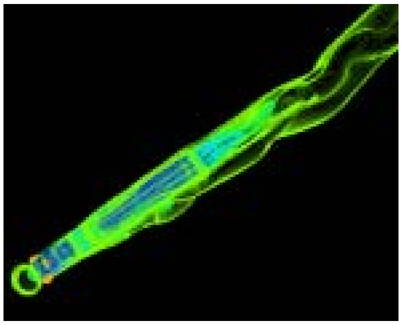
- **GTS Full Vehicle Simulation, NASA 7'x10', 0° and 10° Yaw**
  - **Steady RANS solution**
  - **Turbulence models: *SA*, *SST*, and *k*-w**
- **Trailer Wake Simulations w/ and w/o Boattail, 0° Yaw**
  - **GTS geometry, LES and RANS *SA* & *k*-w**
- **Gap flow, USC modified GTS geometry**
  - **Simulated an unsteady gap flow**
  - **Computationally investigated a gap device**
- **Code Development (leveraged funding)**
  - **Hybrid RANS-LES turbulence model**
- **Discovery Experiment**
  - **LLNL Add-on device investigation and boattail shape optimization**
- **Documentation**
  - **Sandia RANS result on GTS, SAND report**
  - **UEF conference paper**
  - **Finalize RANS result in SAE paper**

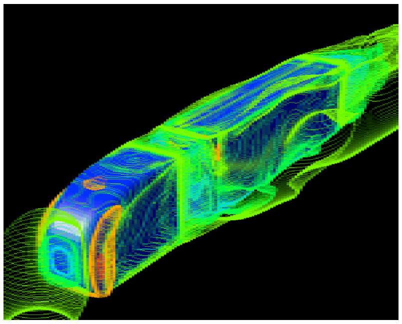
Full Vehicle Simulation, Gap Flow

- Modified GTS model in USC wind tunnel
  - Gap flow investigation
    - Gap distance above critical limit, 0.72
    - Unsteady RANS solution
      - Grid 6.2M elements
  - Gap add-on device
    - Computational investigation of the LLNL gap add-on device

Gap Flow Modeling, 0° yaw

USC modified GTS, Non-Dimensional Gap Distance of 0.72

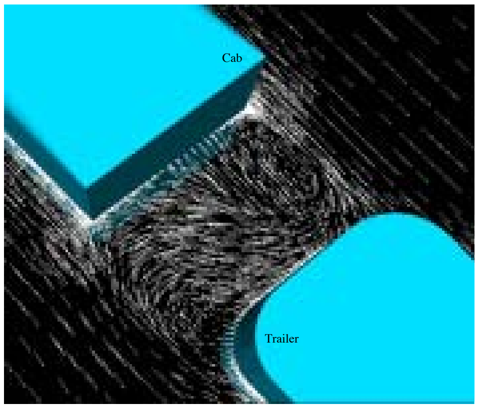




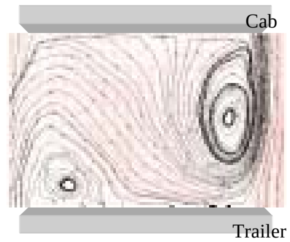
Mach contours

Gap Flow Modeling , 0° yaw, …

Non-Dimensional Gap Distance of 0.72



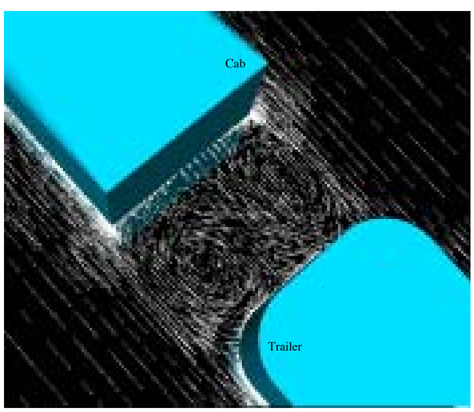
OVERFLOW Computation, 50% Height



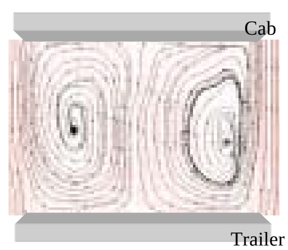
USC Experiment, 50% Height

$$\mathrm{Re} = \frac{U\sqrt{A}}{n} = 300{,}000$$

Gap Flow Modeling , 0° yaw, …



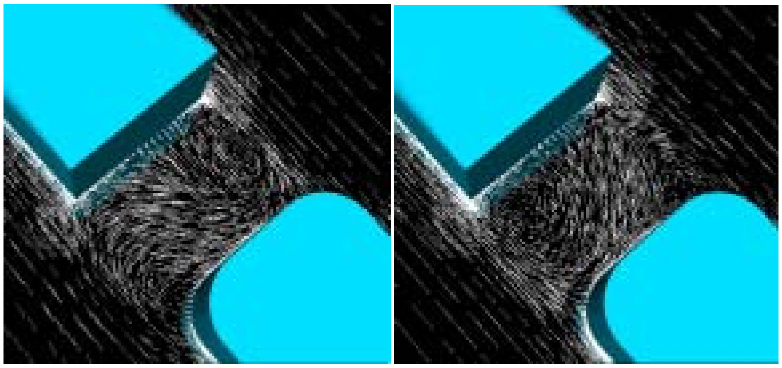
OVERFLOW Computation, 50% Height



USC Experiment, 50% Height

Gap Flow Structure, 0° yaw

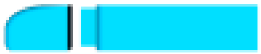
Asymmetric flow structure in the gap on both side



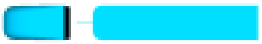
Non-dimensional gap distance of 0.72, USC tunnel condition

LLNL Gap Add-on Device

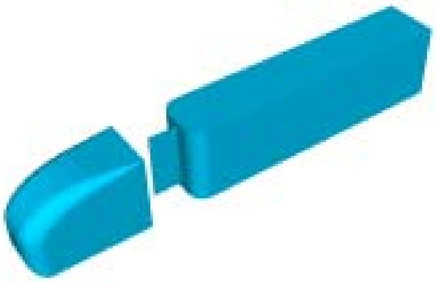
The gap add-on device will stabilize the flow in the gap for the gap distance above the critical limit, and in turn reduces the total aerodynamic drag of the vehicle



Side view

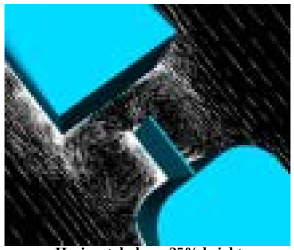


Top view



USC Modified GTS with a Gap Add-on Device

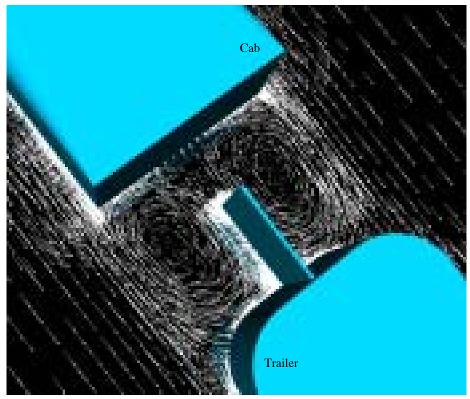
Gap Flow Structure with the Add-on Device



Horizontal plane, 25% height

Horizontal plane, 75% height

0° yaw

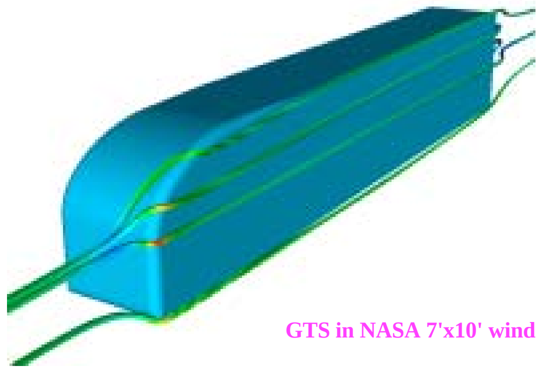


Velocity vector plot, horizontal plane, 50% height

Full Vehicle Simulation

- **GTS model in NASA 7'x10' wind tunnel**
  - **0° yaw**
  - **Turbulence models**
    - **Spalart-Allmaras (*SA*)**
    - **Wilcox k-ω (1988)**
    - **Menter *SST***
  - **Steady RANS solution**
    - **Two grids: 3.7M and 12.2M elements**

Overflow Computational Results, 0° yaw



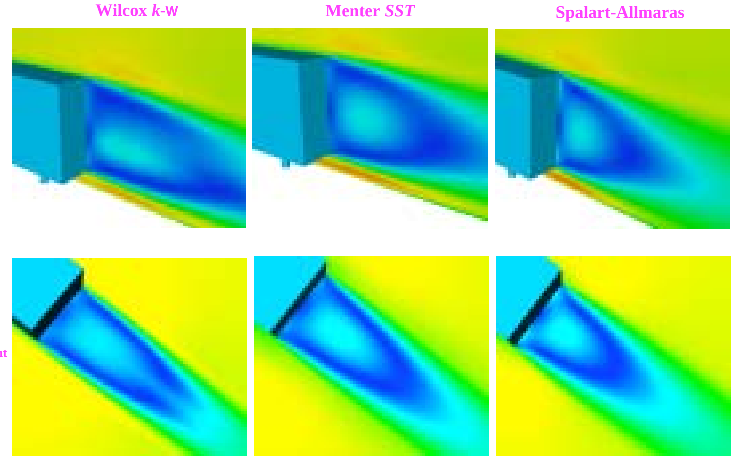
GTS in NASA 7'x10' wind tunnel

Overflow Computational Results, 0° yaw

Wilcox *k*-w | Menter *SST* | Spalart-Allmaras

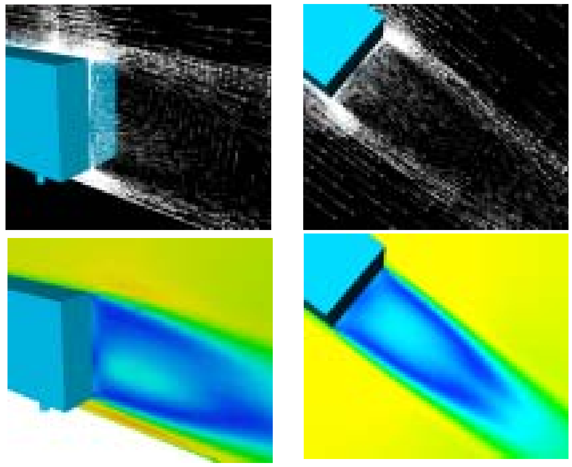
Symmetry Plane

50% Height



Overflow Computational Results, 0° yaw

Wilcox *k*-W turbulence Model

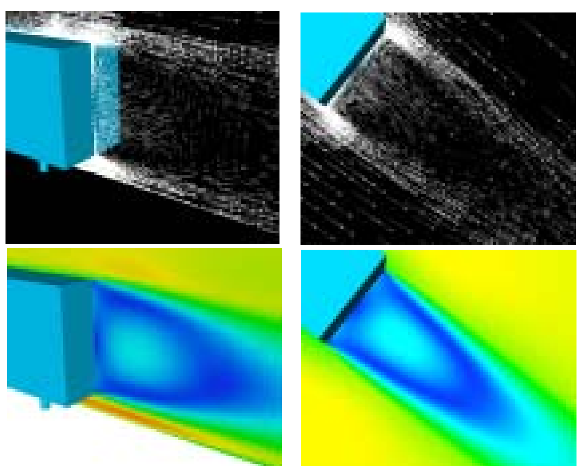


Symmetry plane

50% Height

Overflow Computational Results, 0° yaw

Menter *SST* turbulence Model

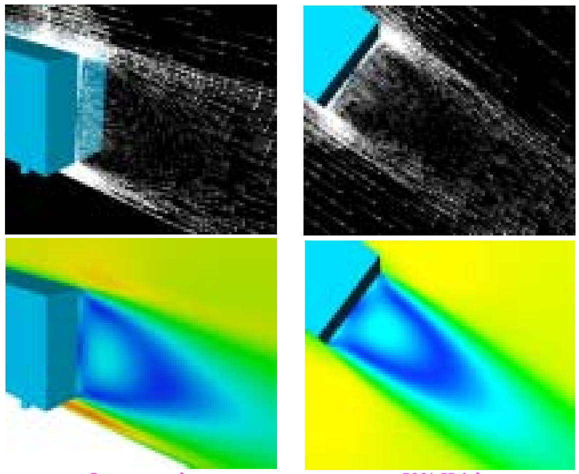


Symmetry plane

50% Height

Overflow Computational Results, 0° yaw

Spalart-Allmaras turbulence Model



Symmetry plane 50% Height

Aerodynamic forces, 0° yaw

Drag	Viscous	Pressure	Total
Wilcox *k*-W, coarse grid	0.103	0.188	0.290
Wilcox *k*-W, fine grid	0.101	0.176	0.277
Menter SST, coarse grid	0.091	0.273	0.364
Menter SST, fine grid	0.092	0.258	0.350
Spalart-Allmaras, fine grid	0.096	0.294	0.390
NASA Experiment, $C_{D,W}$*			0.249
NASA Experiment, $C_{D,R}$*			0.263

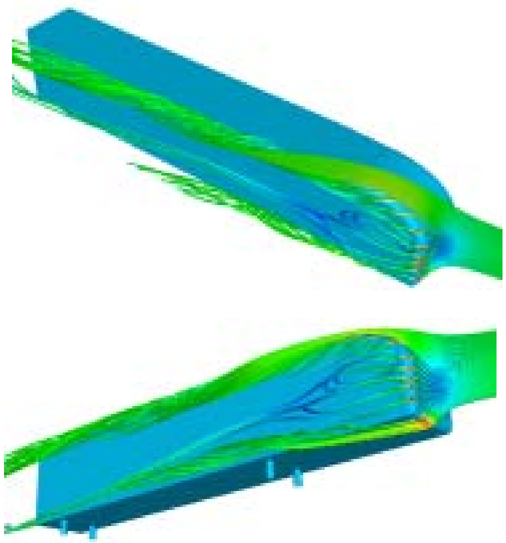
* Subscript W refers to the static pressure measured on the test-section tunnel wall and subscript R refers to the static pressure measured upstream of the test section

Full Vehicle Simulation

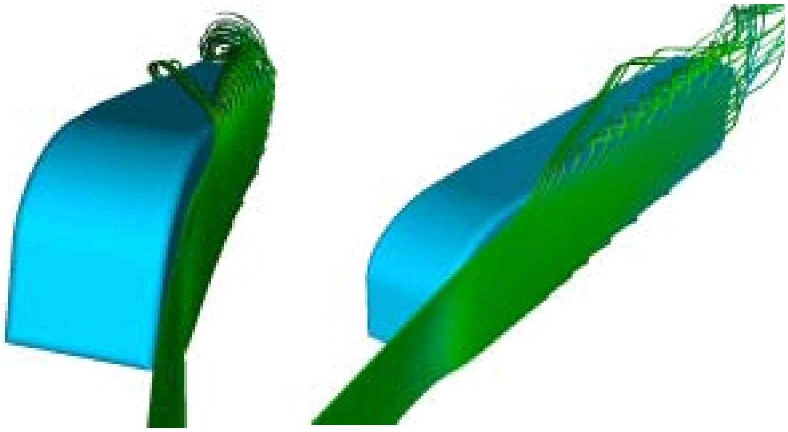
- GTS model in NASA 7'x10' wind tunnel
  - 10° yaw
  - Turbulence models
    - Wilcox *k-w* (1988)
    - Menter *SST*
  - Steady RANS solution
    - Two grids: 3.7M and 12.2M elements

Overflow Computational Results, 10° yaw

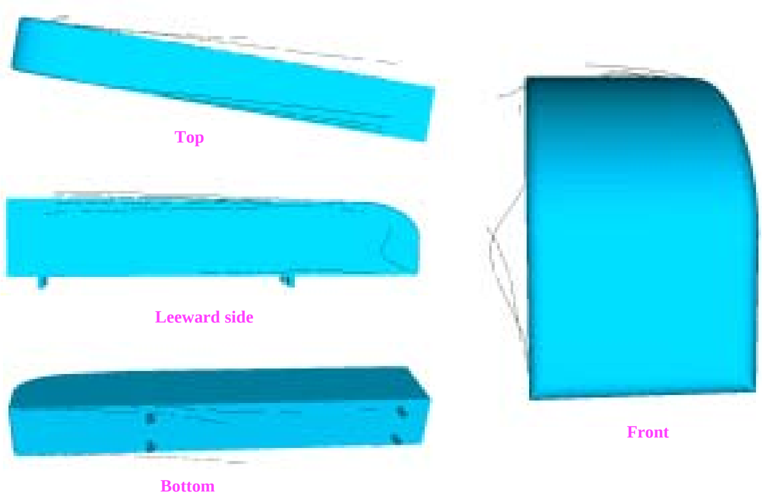
GTS Model



Overflow Computational Results, 10° yaw

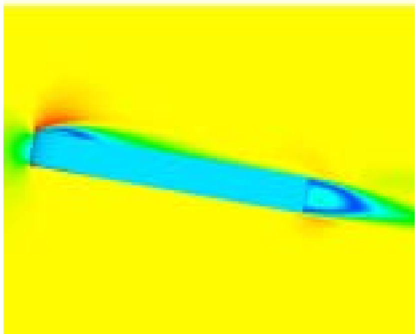


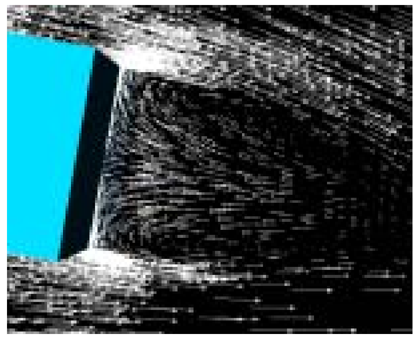
Vortex Core Locations, 10° yaw



Overflow Computational Results, 10° yaw

Wilcox *k*-w turbulence Model, 50% Height

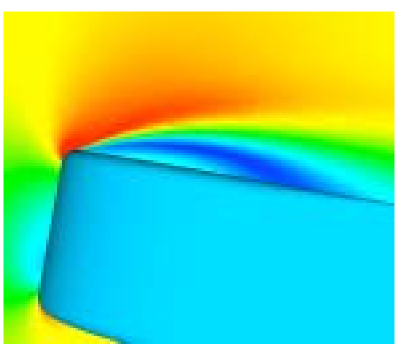


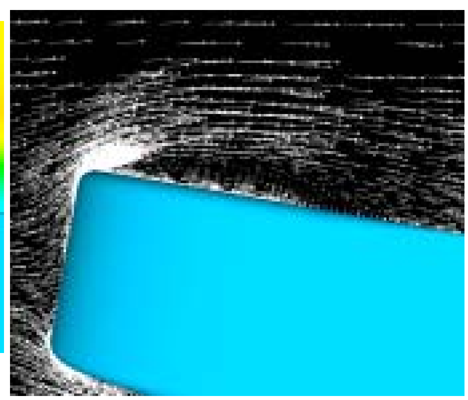


Velocity magnitude contours

Overflow Computational Results, 10° yaw

Wilcox *k*-w turbulence Model, 50% Height





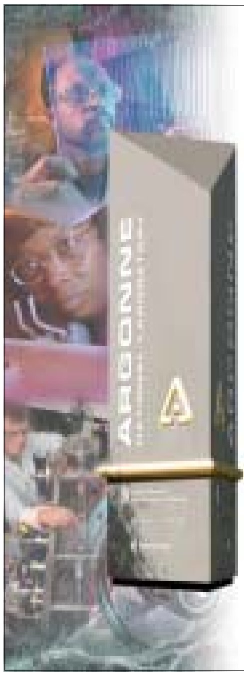
Velocity magnitude contours

Aerodynamic forces, 10° yaw

	Lift	Drag	Side
Wilcox *k*-w, fine grid	-0.004	0.581	1.127
Menter SST, coarse grid	0.006	0.651	1.129
Menter SST, fine grid	-0.010	0.664	1.137
NASA Experiment, $C_{D,W}$	0.021	0.292	1.253
NASA Experiment, $C_{D,R}$	0.022	0.312	1.338

LLNL FY04 Tasks

- **Full Vehicle Simulation**
  - SLRT geometry in NASA 7'x10' wind tunnel
    - Baseline configuration
    - LLNL add-on devices
    - Gap Flow
- **Continue with Modified GTS Gap Flow Investigation**
  - Further investigate/improve the LLNL add-on device
- **Discovery Experiment**
  - Further test the optimized version of the LLNL add-on devices
- **Code Development (leveraged funding)**
  - Hybrid RANS-LES turbulence model development
- **Wheel Well and Underbody**
- **Documentation**
  - RANS/URANS results for GTS in NASA 7'x10' wind tunnel at 0° and 10° yaw, SAE 2004
  - RANS/URANS gap results for modified GTS in USC wind tunnel, SAE



Heavy Vehicle Aerodynamic Drag Prediction

An Assessment of Capabilities in Current Generation Commercial CFD Software

David Pointer,Tanju Sofu, David Weber
Nuclear Engineering Division

Heavy Vehicle Aerodynamic Drag:Working Group Meeting
LLNL

May 30, 2003

Argonne National Laboratory

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Office of Science
U.S. Department of Energy

Outline

- **FY03 Progress**
  - PACCAR CRADA
  - GCM Analysis
- **Remaining FY03 activities**
- **FY04 Plans and Opportunities**
- **Splash and Spray examples**

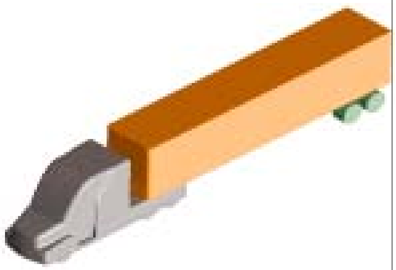
FY03 Progress - PACCAR CRADA

- **CRADA signed in September 2002**
- **Peterbilt-379 geometry identified by PACCAR for experiment**
- **CAD Data provided to ANL in November 2002**
- **Star-CD and PowerFLOW identified as selected software packages**
  - Joint PACCAR-ANL trip to CD-Adapco Group (Star-CD vendor) in November 2002
    - *Training in application of most recently developed tools and applications*
    - *Identification of parameters to be considered in computational studies*
- **Project meeting at PACCAR Technical Center in March 2003**
  - Experimental test plan finalized
  - Parameters for computational effort identified
- **Experiment likely to be delayed until FY04**
  - Preserving budgets as possible to allow for completion as activity

Participants: David Pointer, Tanju Sofu and David Weber
Argonne National Laboratory
Everett Chu, Paul Hancock, and Bob Bundy
PACCAR Technical Center

GCM Analysis

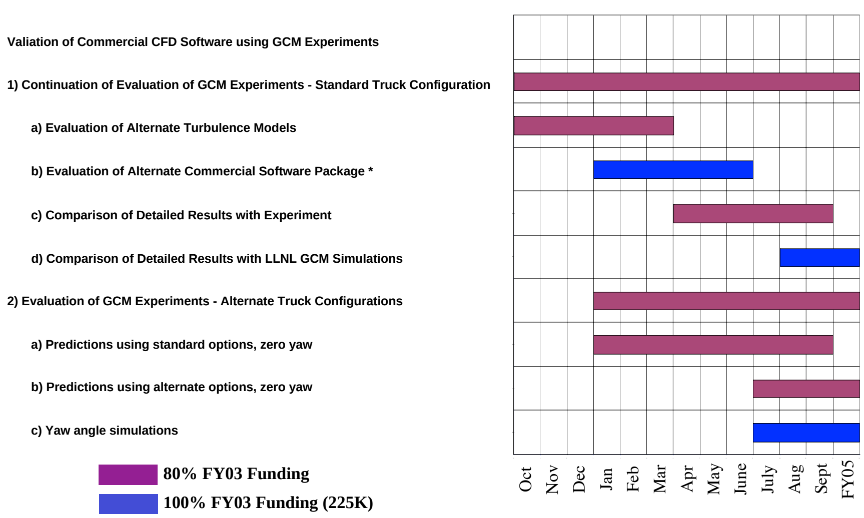
- **Evaluation of solution sensitivities in current-generation commercial CFD software using the standard truck configuration of the Generic Conventional Model (GCM) geometry**
  - Evaluation of results using Star-CD guidelines
    - *Comparison of three standard two-equation turbulence models using wall functions* ✓
  - Mesh sensitivity
    - *Near vehicle cell size*
      - With constant starting surface ✓
      - With surface remapped ✓
      - Successive refinement of single mesh
        - Not practical because of large number of cut cells in r
    - *Near wall cell size* ✓
    - *Initial surface resolution*
  - Computational domain (wind tunnel) size ✓-
  - Yaw angle effects
  - Scalability
    - *Horizontal* ✓
    - *Vertical* ✓



Remaining FY03 Activities

- **PACCAR CRADA**
  - Evaluation of empty wind tunnel geometry
  - Development of computational meshes
- **GCM standard truck configuration simulation efforts – Phase I**
  - Compare results with detailed pressure data
  - Look for ways to better evaluate quality of flow field prediction
  - Evaluation of solution sensitivity to underbody refinement level
    - *Standard Truck Configuration*
    - *Standard Truck Configuration with additional structure under trailer (requested by PACCAR)*
  - Yaw Angle Analyses (continuing into FY04)
    - *Use pseudo-transient methodology*
      - Steady state in each yaw angle position
      - Fully transient moving mesh model to capture transition between position

Proposed FY04 Effort



* Assuming PowerFLOW Demonstration License is Extended

Additional/Alternate FY04 Activities

- **Numerical Evaluation of Pneumatic Devices for Reduction of Heavy Vehicle Aerodynamic Drag**
  - Phase I: Evaluation of GTRI Wind Tunnel Experiments
    - *Develop computational model of vehicle and device geometry (3/04)*
    - *Simulate selected wind tunnel experiment cases and evaluate drag coefficients (6/04)*
    - *Evaluate confidence in results through sensitivity studies (9/04)*
  - Phase II: Evaluation of Full Scale Experiments
    - *Develop computational model of vehicle and device geometry*
    - *Simulate selected test track conditions and evaluate drag coefficients*
    - *Evaluate confidence in results through sensitivity studies*
  - Phase III: Parametric Optimization of Device
    - *Identify design parameters and develop test matrix based upon previous phases*
    - *Simulate selected parametric cases and evaluate drag coefficients*
    - *Provide recommendations for device optimization and improvement*
- **Likely completed in collaboration with University of Illinois at Chicago**

Aerodynamic Drag Reduction for Open Top Rail Cargo Containers (Coal Cars)

- **Significant increase in fuel use is seen when open top cargo containers are hauled empty rather than full**
- **Covers alleviate problem but are an unattractive option**
  - Additional labor, maintenance cost
  - Reduced cargo capacity
- **Propose the development of passive, unobtrusive flow filed enhancement devices**
  - Simulate flow field around empty and fully loaded cargo containers under typical transit conditions
  - Suggest and evaluate changes in flow field that may result in reduced drag losses
  - Development devices to enable these changes to the flow field without significantly impacting mode of operation
- **Proposed 3 year study funded as an internal Transportation Technology Initiative**
  - In partnership with ANL's Transportation Technology Center
  - Possible partnership with BNSF